Machine learning based DWDM design using regression modelling

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Abstract: In this paper, we discuss the non-linearity problems such as Four Wave Mixing (FWM) and high signal distortion with low Output Signal to Noise Ratio (OSNR) in the design of a 64-channel DWDM system using Regression learning technique. The occurrence of FWM in a DWDM system with high number of channels reduces the performance of an optical fiber system in terms of bandwidth and increases computational complexity. High signal distortion with low OSNR reduces network throughput, energy efficiency and thus forces re-transmission. To overcome the above problems, DWDM system with higher number of channel necessitates an optimized design based on correlation factors of optical dependent and independent variable factors such as BER, Q-factor, signal power, noise power and OSNR. Proposed here is a regression optimized DWDM system design. Regression is used here for correlating and optimizing the optical parameters. In this paper, the problem of non-linearity is solved through optimized DWDM design based on correlated parameters in 16, 32 and 64-Channeled DWDM system. The regression based correlated DWDM design (R-DWDM) is improvised mechanism over the independent parameter based simulations and thus improves accuracy. The R-DWDM design system shows higher accuracy through the derived R-value for optical parameters such as input power, channel spacing, optical gain and data rate. The enhancement achieved through the regression based optimized DWDM design is evaluated in terms of optical measurements such as signal power, noise power, Q-factor and BER.

Key words: Optical parameters, FWM, DWDM, Regression modeling, Correlation.

I. Introduction:-

DWDM system in optical networks provides high data rate for long distance and ultra-speed transmissions. In optical network, optical signal are sensitivity to group velocity dispersion, dependence on scattering and refractive index. The above parameters introduces fiber non-linearities (FWM) in the optical network and it is a challenging problem. The efficiency of the optical communication system is measured based on reduced fiber nonlinearities [1]. Furthermore, the non-linearities in DWDM optical communication leads to Four Wave Mixing (FWM), cross phase modulation (XPM) and self-phase modulation (SPM), which affects the speed with haul data transmission [6].

Researchers proposes various techniques in WDM design to avoid the non-linearities in DWDM [3]. The techniques are hybrid dispersion compensation using WDM/ TDM techniques [4], FBG with gain Flattening Filter, Unequal channel spacing [13], Combination of optical phase conjugator and DCF with FBG[2], Different fiber types with hybrid amplifier and dispersion management[5], Asymmetrical dispersion managed fiber[7] for sub-plank higher-order dispersion [9], DWDM system design using different NZDSF shifted fibers[8]. Hybrid optical amplifiers for DWDM system with ultra-small channel spacing [16], PMD Emulator based two-way ultra DWDM passive optical networking (PON) [17]. DWDM system design with Rectangular optical filter at receiver end [11] are designed to improve signal quality.
To reduce the design complexity of DWDM systems, analytical model demands more efficient algorithms based on Artificial intelligence (AI) and Machine Learning (ML). The machine learning algorithms can provide more accuracy and shows the relationship between the optical input parameters. ML algorithms provides efficient design values for optical amplifier controls modulation format recognition, and optical performance monitoring [14]. ML technique is used to characterise and mitigate the power excursion of WDM with 1% error accuracy [15].

**Problem:**
1. To identify the influencing parameters of FWM in DWDM is done through iterative simulations, which affects the accuracy level in optical data transmission.
2. The iterative simulation for the effective design of DWDM fails to provide higher bandwidth and bit rate, since the optical parameters in the device such as input power, channel spacing, data rate, modulation format and optical gain changes according to the input parameters.
3. The customized design of DWDM based on real time environment is a challenging task.

**Motivation:**
1. The DWDM design is based on machine learning algorithms such as regression model for reducing the FWM with more accuracy. Regression modeling avoids the huge quantity of iterative calculations generally involved in the design and testing of a DWDM system.
2. The regression model based DWDM design is customized based on identification of the optical independent and dependent parameters. The independent and dependent parameters are classified based on R-value relations established between the optical parameters such as input power, channel spacing, data rate, modulation format and optical gain are Max Q-factor, Min BER, OSNR, signal power and noise power.
3. The regression modeling R-Values shows the relationship between the optical parameters and identifies the parameters, which increases the FWM.

This paper is organised as follows, section II presents the related works for the problem identified. Inferences from literature survey is discussed in section III. Section IV presents materials, method, and section V presents proposed R-DWDM system design. Mathematical analysis of FWM influencing factors is discussed in section VI. Section VII describes results and discussion for regression-based analysis of different parameters and its influence over FWM. The estimated R-Values for various factors such as BER, Q-factor, output signal power, OSNR, noise power and their relationship with arbitrary parameters for all the three different channel capacities with simulated results and predicted results are also discussed in section VII. Section VIII concludes the work and presents the future scope.

**II. RELATED WORK:**

| Author/Year/Reference | WDM design Techniques Features & advantages | Remarks |
|-----------------------|--------------------------------------------|---------|
| E.Pincemin et.al [/2004] /[5] | Minimizes FWM power and reduces dispersion. | Perform less in varying channel space & difficult for sectioning. |
| M.Noshad et.al / [2012] /[7] | Improves the power level and SXR (23dB) | To improve power needs repeated simulations to fix the design. |
| A. Monika, et.al / [2013]/[9] | Optimized parameters for long distance transmission with below FWM by 10-15db. | Inefficient utilization of bandwidth. |
| G. Kaur et.al / [2014] / [2] | Attains FWM power for OPC (-49.73dBm) and FBG (-18.75dBm) Supresses FWM ≥ 40dBm | Consumes more power and less throughput. |
| Authors                  | Description                                                                 | Notes                                                                 |
|-------------------------|-----------------------------------------------------------------------------|----------------------------------------------------------------------|
| S. Singh et.al [2014]   | High flat gain in 0.2nm channel spacing.                                    | Induces distortion in pulse and more cross talks due to non-linearities. |
| S.E.Karlık et.al [2016] | High bit rate and less dispersion- 0.4 b/s/Hz spectral efficiency and 100-GHz as channel spacing. | Affects inter channel non-linearities and high frequency shift.        |
| W.S.El-Deeb.et.al [2016] | Rectangular optical filter is used to improve signal Quality.               | Need feedback system to analyze transmission characteristics.         |
| Shaymaa et.al [2017]    | FBG with less number of optical fibers and customized design.               | High interaction of self-phase modulation.                           |
| Ajmani et.al [2019]     | Performs parametric optimization to meet constraints of Q-factor and Min BER values. | Less feasibility of these components for more conjugational simulations. |
| Kathpal et.al [2019]    | Analytical validation is performs at 0dBm input power to achieve FWM power in 4dBm with. | Implementation is difficult due to its more number of channel with external modulation. |
| Sabapathi.T et.al [2019] | Optimized input power and circular polarizers used to avoid FWM and SRS effects. | High spectral transmission leads to more power consumption.          |
| Obaid et.al [2019]      | Lowest gain ripple (1.70 dB) and Noise Figure (4dB) achieves with 0.2nm channel spacing. | Occurrence of high inter channel nonlinearities.                     |
| Yıldırım et.al [2019]   | Performs better for Kerr and parabolic law nonlinearities.                  | Excessive power loss and limited in one dimension.                   |
| Manzoor.et.al [2019]    | Achieves down link (7dB) and uplink (5dB) FWM efficiency improved in 25Ghz channel spacing. | Lack of stability, repeatability and absence of tunable average differential group delay. |
| D.Uzunidis.et.al [2019] | Validates the accuracy of a closed-form formula with QPSK modulation format. | Short span length < 30km                                             |
| Manzoor.et.al [2020]    | Low input with high gain amplifier, DWDM and OTDM combined with circular polarization. | Efficiency depends on light polarization state.                      |

**R-DWDM method:**

- **Dependent parameters of R-DWDM:**
  - BER, Q-factor, signal power, noise power and OSNR.

- **Independent parameters of R-DWDM:**
  - Input power, channel spacing, bit rate, optical gain and RZ modulation format with duty cycle.

**Method:** Regression modeling

**Advantages of R-DWDM:**

- Avoids “n” number of bit rate iteration in simulation.
- Customized design of DWDM system design based on real time field requirement.
- Simple structure to implement. High-level accuracy. Reduce run time errors and calculations.

Table 1: Related Work
III. INFERENCES FROM LITERATURE SURVEY:
FWM in high capacity DWDM system provides inter channel interferences and causes more cross talk, which affects network throughput and lowers energy efficiency. More number of DWDM channel consumes more power and shows high signal distortions with low OSNR, which reduces DWDM network performance and increase computational complexity. Optimization of DWDM system parameters requires machine-learning techniques to improve accuracy and Quality of data transmission. In this paper, we propose a regression based DWDM (R-DWDM) system, which avoids more number of iteration and provides customized design based on real time field requirement. This paper also provides simple efficient structure of DWDM system with High-level accuracy and reduce run time computational errors.

IV. MATERIALS AND METHOD:
The Optical system consists of WDM transmitter, WDM multiplexer, SMF, Optical amplifier, Dispersion compensation fiber, WDM demultiplexer, photodetector, Bessel LPF and BER analyser. WDM transmitter consists of the parametric configurations such as 10 Gbps data rate at input source, channel input power -10dBm (0.1mw), and channel spacing of 100 GHz with NRZ Modulation format. The transmitter perform the modulation using Light signals for the input data sequences.

The modulated data sequences from the WDM transmitter pass through the WDM multiplexer with channel spacing of 100GHz and Bessel filter as shown in fig 1. WDM multiplexed signal transmit through the single mode fiber (SMF) of length 100 km. SMF consists of parameters such as dispersion coefficient of 16.75 ps/nm/km, attenuation coefficient of 0.2 dB/km, dispersion slope 0.075 ps/nm^2/km, Beta2 is -20 ps^2/km, differential group delay 0.2 ps/km and PMD coefficient 0.01 ps/sqr (km) is employed.

The signals from the SMF fed to Optical amplifier for amplification with gain of 20 dB. Further, the signal transmit through Dispersion compensation fiber (DCF) to avoid FWM losses. Then amplified signal transmit through the Dispersion compensation fiber of length 20.93km. The DCF consists of attenuation coefficient of 0.2 dB/km, differential group delay 3 ps/km and PMD coefficient 0.01 ps/ (km)^0.5.

In the receiving end, WDM demultiplexer receives filtered signal from DCF for the demultiplexing signals. The demultiplexed signal transmit through photodetector for converting light into electrical Signal with dark current 10nA, thermal power density 100e-024 W/Hz and PIN Responsivity 1 A/W. Electrical signal transmits through the Bessel LPF and received at BER analyser.

V. PROPOSED R-DWDM DESIGN:
Fig.2 presents Functional schematic set-up for parametric analysis. This is structured by analyzing linking, input and output parameters discussed in simulation setup. The proposed R-DWDM functional diagram is shown in fig 2. R- DWDM consists of independent parameters such as Bit rate, channel spacing, input power, and modulation format. The dependent factors in R-DWDM are Max Q-factor, Min BER, noise power and OSNR that mainly mitigates FWM. The regression modeling simulations are performed for different independent and dependent parameters and identifies the strong correlation between the parameters through R- Value 0.8. The flow of this simulation process is presented in fig 3. In proposed R-DWDM method, the customized design of DWDM is developed, based on the real time field requirements. The R-DWDM design is to tune the parameters such as input power, channel spacing, bit rate, and optical gain, after analyzing the behaviour of FWM according to the variations in the parameters. During the analyses, the relation between the various parameters, FWM and its impacts over the DWDM channel capacity and bandwidth stabilization is modeled. The modeling is done through the regression analysis to identify the dependent and independent parameters for effective DWDM output in the real time field. The real time field factors are Min BER, Max Q-factor, signal power, noise power and OSNR to mitigate FWM.
The proposed R-DWDM system is shown in fig 2 with dependent and independent parametric iterative simulation model. The R-Value shows the relations between the parameters is an optical system such relations established for designing the proposed R-DWDM design. R values calculated from regression modeling for the parameters such as Min BER, Max Q-factor, signal power, noise power and OSNR as dependent variables, whereas the input power, channel spacing, optical gain, modulation format and bit rate are independent variables.

In fig 4, the calculations perform through regression modeling. For example, in 16-channel the equation is \[ \text{Output signal power} = 1.0909 \times (\text{input power}) + 15.4109 \] and R has 0.9447. Now the above equation studies the relation between the output signal power and input power through R-value. The R-value with 0.9447 shows the strong relation between the input power and output signal power whereas, Output signal noise ratio: \[ 0.1887 \times (\text{Input power}) + 52.3411 \] and has R-value 0.4243 and proves less relationship between input power and output signal to noise ratio. Similarly for 32 channel regression equation is Output signal power: \[ 1.000 \times (\text{Input power}) + 16.3386 \] and R value 1.000, proves strong relationship between the input power and output signal power. The 32 channel regression equation for Output signal noise ratio: \[ 2.69 \times 10^{-4} (\text{Input power}) + 55.9361 \] and R-value 0.0625 proves no strong correlation between input power and output signal noise ratio. For 64 channel, the equation is Output Signal Power: \[ 1.000 \times (\text{Input power}) + 21.1632 \] with R-value 1.000, shows strong correlation between the input power and output signal power and the equation for Output Signal Noise Ratio: \[ -0.0059 \times (\text{Input power}) + 50.6187 \] and R-value -0.2390 for 64 channel shows weak correlation between input power and output signal to noise ratio.

VI. Mathematical Analysis of FWM influencing Factors
FWM distortion in DWDM system depends on the number of transmitted input channels. The relationship between FWM factors and number of input channels is given by the equation, \[ m = \frac{n^2}{2(n-1)} \] \( m \) - denotes number of FWM factors and \( n \) the number of Input channels. Moreover, data rate increases with additional channels and influences BER, Q factor. The influencing parameters increases more FWM factors. Furthermore, optical amplifier with higher bit transmission leads to amplified spontaneous emission noises. These noises results in calculation of Output Signal to Noise Ratio (OSNR) and calculated as in equation 2.1

\[ \text{OSNR}_n(n) = \frac{u_i(n)}{n \sigma + \sum_{i \neq j} u_j(n)} \]  
(2.1)

Where \( u_i(n) = \text{input power of the } i_{th} \text{ channel}, \sqrt{ij} \text{: } j^{th} \text{ noise gain of } i_{th} \text{ channel and } n \sigma : \text{ is noise at transmitter.} \) The Effective SNR is calculated as in equation 2.2

\[ \text{SNR} = \frac{P}{\sigma^2_{\text{ASE}} + P_{\text{ASE}}^2} \]  
(2.2)

\( P \) is average signal power, \( \sigma^2_{\text{ASE}} \) denotes noise power due to amplified spontaneous emission (ASE) and \( x_{NC} \) is the nonlinear coefficient. Average signal power show well-known system performance for SNR calculated from equation 2.3

\[ \text{Peak SNR} = (\sigma^2_{\text{ASE}}/\sigma^2) \times 2 \times 3 \times x_{NC}^{-1/3} \]  
(2.3)

Fiber optic gain is mathematically express as,

\[ G = (P_{\text{out}} - P_{\text{ASE}})/P_{\text{in}} \]  
(2.4)

Where \( P_{\text{in}}, P_{\text{out}} \) are input and output signal power and \( P_{\text{ASE}} \) is ASE noise power.

Q- Factor and BER are calculated from equation (2.5) and (2.6)

\[ Q = \frac{I_i - I_0}{\sigma_1 + \sigma_0} \]  
(2.5)

\[ \text{BER} = \frac{1}{2} \text{erf} \left( \frac{q}{\sqrt{2}} \right) \]  
(2.6)

Where \( I_i \) and \( \sigma_1 \) are the mean value and variance output of Gaussian pulse 1. \( I_0 \) and \( \sigma_0 \) are the mean and variance output of Gaussian pulse 0.

VII. Results and Discussion:-
In this section, simulation of R- DWDM system using regression algorithm is developed to understand the characteristics of FWM and correlation factors. The correlation factors will study the
influencing parameters of FWM. The analysis is carried out to identify and characterize the relationship of FWM issues with the multiple factors such as Max Q-factor, Minimum BER, output signal power, Noise Power, and OSNR and their relations in influencing the FWM.

Regression R-value provides the correlation and shows how the factors such as output signal power, noise power, OSNR, Q-factor, eye diagrams characteristics are related to the arbitrary parameters such as input power, channel spacing, optical gain, bitrate, duty cycle and core size of optical fiber. Henceforth the term “factors” is used for max Q-factor, minimum BER, output signal power, noise power, and OSNR and the term “parameters” is used as input power, channel spacing, optical gain, bit rate, duty cycle and core size of optical fiber. The calculated R-value and the correlations are classified as shown in table.2.

| S.No | R-value | Level of Correlation |
|------|---------|----------------------|
| 1.   | 1 ≥ 0.8 | High                 |
| 2.   | 0.7 ≥ 0.5 | Moderate          |
| 3.   | 0.4 ≥ 0.3 | Low                |
| 4.   | 0.2 ≥ 0.1 | Very low           |
| 5.   | R value is negative | No             |

Table.2 Correlation levels of estimated R-values

The Iterative simulations are run in the setup by varying parameters for each of the different factors and calculated the R-value through regression algorithm. For example, simulation setup for 32-channel DWDM system is developed in OptiSystem. Input independent parameters such as Channel spacing varies from 25GHz to 100 GHz and results are observed for the dependent factors such as output signal power, noise power, OSNR, Max Q-factor and Min BER. Results are tabulated as in table.3

| Channel spacing (GHz) | Signal Power (dBm) | Noise Power (dBm) | OSNR(dB) | Max Q-factor | Min. BER | Eye height |
|-----------------------|--------------------|-------------------|----------|--------------|----------|------------|
| 25                    | 6.328677           | -14.7164          | 21.0451  | 7.95723      | 0.00155  | -1.32E-05  |
| 50                    | 6.327733           | -17.4343          | 23.76208 | 16.2035      | 4.30E-91 | 0.000253   |
| 75                    | 6.327607           | -17.4412          | 23.76877 | 23.8282      | 7.82E-171| 0.000269   |
| 100                   | 6.327578           | -49.6169          | 55.94446 | 30.3044      | 1.11E-141| 0.000265   |

Table.3 simulated dataset of 32-channel for regression modeling under different channel spacing

The regression equation is developed for R-DWDM system based on the table 7.1. The channel spacing of 50GHz for 32 channel has output Signal Power = $-1.362 \times 10^{-5} \times (\text{Channel spacing}) + 6.328$ and R-value 0.8447. From the table.3, the channel spacing and output signal power is correlated for the above equation. The relationship between channel spacing and output signal power is proved to be strong because of R-value 0.8447. The regression model equation applied for various channel spacing and output signal power to predict the results without simulation and the same is shown in table.2 as predicated value. Similarly, the predicted value is also verified for accuracy after simulating the same parameter, which is given as an input to the regression equation. Similarly, the regression equation for 16, 32 and 64 channel and relating simulated results, predicted values with their respective R-value is shown in table.4.

From the study, the predicted and simulated value with R-value shows that input power influences nonlinearities in DWDM and linearly proportional to FWM. Lowering input power decreases output signal power and hence OSNR decreases as in equation (2.1).

From the eye diagram as shown in fig.5, results are observed for different channel sizes of a DWDM on an output spectrum analyser. The iterative calculations for factors such as Q-factor, BER and eye
height leads to understand the significant changes in dispersion. These are listed in fig.5. From this analysis, lowering the transmitter input power, reduces the FWM marginally. When input power goes low then there will be a prominent degradation of BER, eye height, and Q factor. Simulations for regression calculations for different channel capacities shows that the input power has high level of correlation to the system factors such as output signal power, noise power, OSNR, and Q-factor, which is proven by the R-value, and can be seen in table.4. From the estimated R-values, it is learnt that a linear relationship exists between the number of channels in a system and output signal power, noise power and eye height. Relationship is inverse for factors such as Q-factor and OSNR. Fig.5 shows the eye diagram of varying input power ranges such as -10dBm, 0dBm, and 10dBm.

| Channel | Regression Modeling Equation | R value | Simulated results | Predicted regression results |
|---------|--------------------------------|---------|-------------------|----------------------------|
| 16-channel | Output Signal Power : 1.0909 × (Input power) + 15.4109 | 0.9447 | 26.31987 | 26.3199 |
|         | Noise Power : 1.0005 × (Input power) + (-39.8195) | 0.5136 | -29.8283 | -29.8145 |
|         | Output Signal Noise Ratio : 0.1887 × (Input power) + 52.3411 | 0.4243 | 56.1432 | 54.2281 |
|         | Quality Factor : 0.1183 × (Input power) + 26.7695 | 0.6473 | 28.3853 | 27.9527 |
|         | Eye Height : 0.0011 × (Input power) +0.0066 | 0.8784 | 0.026964 | 0.0176 |
| 32-channel | Output Signal Power : 1.000 × (Input power) + 16.3386 | 1.000 | 26.33841 | 26.3386 |
|         | Noise Power : 0.9997 × (Input power) – 39.5976 | 1.000 | -29.5754 | -29.6006 |
|         | Output Signal Noise Ratio : 2.69×10^-4 × (Input power) + 55.9361 | 0.0625 | 55.91382 | 55.93874 |
|         | Quality Factor : 0.0806 × (Input power) + 26.6422 | 0.3726 | 28.4121 | 27.4482 |
|         | Eye Height : 0.0011 × (Input power) + 0.0065 | 0.8593 | 0.026881 | 0.0175 |
| 64-channel | Output Signal Power : 1.000 × (Input power) + 21.1632 | 1.000 | 11.16277 | 11.632 |
|         | Noise Power : 1.0006 × (Input power) – 29.4564 | 1.000 | -39.4845 | -39.4564 |
|         | Output Signal Noise Ratio : -0.0059 × (Input power) + 50.6187 | -0.2390 | 50.64678 | 50.6777 |
|         | Quality Factor : 0.5007 × (Input power) + 86.8689 | 0.3256 | 78.7751 | 81.8619 |
|         | Eye Height : 0.0132 × (Input power) + 0.0853 | 0.8647 | 0.002918 | -0.00467 |

Table.4 Estimated regression equations and their R-value for Input power with simulated and predicted results.

Similarly, the table.5 shows the effects of channel spacing on the various factors for three different channel capacities with R-value and their simulated and predicted regression results. In this setup, R-DWDM is performed by varying channel spacing from 25GHZ to 100GHZ for all three different channel configurations. Channel spacing has inverse proportionality relationship with the factors influencing FWM. Increasing the channel spacing minimizes FWM effect and produces high BER and low Q-factor. Higher the number of channels, higher
is the interference between adjacent channels and results to elevate FWM issues. Low channel spacing in DWDM systems results in decreasing Q-factor, increased noise power and it adversely influences OSNR.

FWM effects are enhanced with narrow channel spacing and requires high considerations in a DWDM system. From the eye diagram, it is observed that lower channel spacing with high input power can accommodate more number of channels but at the cost of decreased eye height. From the analysis, it can be studied that increasing channel spacing correlates highly to factors such as output signal power, Q-factor, and eye spectral characteristics resulting in reduced FWM. Increasing channel spacing will reduce noise power that will directly create positive impact over OSNR. Fig.6 shows the eye diagram characteristic for the factors obtained with different channel spacing for a 64-channel. It can be observed that the eye height is better when the channel spacing of 100GHZ. Resulting in better Q-factor, but this is trade-off parameter and needs to be decided as per the system requirements.

| Channel & specification | Regression Modeling Equation | R value | Simulated results | Predicted regression results |
|-------------------------|------------------------------|---------|-------------------|----------------------------|
| 16-channel & 100GHz channel spacing | Output Signal Power : 1.86x10^{-3} × (Channel spacing) + 6.3104 | 0.75795 | 6.311936 | 6.4964 |
|                         | Noise Power : -0.4159 × (Channel spacing) + 0.9322 | -0.8121 | -49.7879 | -40.6578 |
|                         | Output Signal Noise Ratio :0.4159 × (Channel spacing) + 5.3782 | 0.8122 | 56.09988 | 46.9682 |
|                         | Quality Factor : 0.2944 × (Channel spacing) + 0.2625 | 0.8710 | 25.4123 | 29.7025 |
|                         | Eye Height : 3.018x10^{-6} × (Channel spacing) + 1.21x10^{-5} | 0.7948 | 0.000264 | 0.000313 |

| 32-channel & 50GHz channel spacing | Output Signal Power : -1.362x10^{-5} × (Channel spacing) + 6.328 | 0.8447 | 6.32773 | 6.327319 |
|                         | Noise Power : -0.4188 × (Channel spacing) + 1.3749 | -0.8147 | -17.4343 | -19.5651 |
|                         | Output Signal Noise Ratio :0.4188 × (Channel spacing) + 4.9539 | 0.8147 | 23.76208 | 25.8939 |
|                         | Quality Factor : 0.29987 × (Channel spacing) + 0.4068 | 0.8605 | 16.2035 | 15.9573 |
|                         | Eye Height : 3.0856x10^{-6} × (Channel spacing) + 7.2x10^{-6} | 0.7983 | 0.000253 | 0.00016856 |

| 64-channel & 25GHz channel spacing | Output Signal Power : -1.251x10^{-5} × (Channel spacing) + 11.2381 | 0.8943 | 11.17792 | 11.237787 |
|                         | Noise Power : 0.04188 × (Channel spacing) + 1.2376 | -0.8093 | 2.357671 | 2.2846 |
|                         | Output Signal Noise Ratio :0.07188 × (Channel spacing) + 5.9921 | 0.8090 | 8.820248 | 7.0391 |
|                         | Quality Factor : 0.03415 × (Channel spacing) + 1.5037 | 0.9478 | 2.55866 | 2.35745 |
|                         | Eye Height : 1.837x10^{-6} × (Channel spacing) + 5.2x10^{-6} | 0.7954 | 0.00051 | 0.00051125 |

Table.5 Estimated regression equation and their R-value for Channel spacing with simulated and predicted results

Similarly, Table.6 shows the effects of optical gain on the various factors for three different channel capacities with R-value and simulated and predicted regression results.
| Channel & specification | Regression Modeling Equation | $R$ value | Simulated results | Predicted regression results |
|-------------------------|-----------------------------|-----------|------------------|-----------------------------|
| 16- channel & 40dB optical gain | Output Signal Power : $1.000 \times (\text{Optical Gain}) + (-13.6857)$ | 1.000 | 26.31495 | 26.3143 |
| | Noise Power : $1.0010 \times (\text{Optical Gain}) + (- 69.8389)$ | 1.0000 | -29.7971 | -29.7989 |
| | Output Signal Noise Ratio : $-0.0010 \times (\text{Optical Gain}) + 56.1532$ | -0.9050 | 56.11204 | 56.1132 |
| | Quality Factor : $0.1720 \times (\text{Optical Gain}) + 21.1753$ | 0.4245 | 24.7843 | 28.0553 |
| | Eye Height : $0.0012 \times (\text{Optical Gain}) + (-0.0282)$ | 0.8684 | 0.02634 | 0.0198 |
| 32- channel & 20 dB optical gain | Output Signal Power : $1.000 \times (\text{Optical Gain}) + (-13.6706)$ | 1.000 | 6.3295 | 6.3294 |
| | Noise Power : $0.998 \times (\text{Optical Gain}) + (- 69.6024)$ | 1.000 | -49.6125 | -49.6124 |
| | Output Signal Noise Ratio : $2.094\times10^{-4} \times (\text{Optical Gain}) + 55.932$ | 0.1598 | 55.9420 | 55.93221 |
| | Quality Factor : $0.1412 \times (\text{Optical Gain}) + 22.3975$ | 0.3978 | 24.0227 | 25.2215 |
| | Eye Height : $0.0012 \times (\text{Optical Gain}) + (-0.0282)$ | 0.8687 | 0.0002 | -0.0042 |
| 64- channel & 30dB optical gain | Output Signal Power : $1.000 \times (\text{Optical Gain}) + (-23.8456)$ | 1.000 | 6.154065 | 6.1544 |
| | Noise Power: $1.001 \times (\text{Optical Gain}) + (-74.4771)$ | 1.000 | -44.4667 | -44.4471 |
| | Output Signal Noise Ratio : $-9.60\times10^{-5} \times (\text{Optical Gain}) + 50.6316$ | -0.0625 | 50.62073 | 50.62872 |
| | Quality Factor : $3.010 \times (\text{Optical Gain}) - 20.2516$ | 0.9699 | 73.9029 | 70.0484 |
| | Eye Height : $4.20\times10^{-4} \times (\text{Optical Gain}) - 0.0099$ | 0.8640 | 0.0009 | 0.0027 |

Table 6: Estimated regression equation and their R- value for Optical gain with simulated and predicted results.

The listed equations in table 6 by using optical gain as the parameter under study keeping all other parameters constant. Semiconductor laser optical amplification characteristic is considers in the form of optical gain. Recombination of electrons and holes of simulated emission improves optical gain.

Optical gain and output signal power are directly proportional factors leads to increase gain, good spectral characteristics and hence reduces FWM. This comparative study shows that gain of optical fiber varies from 20dB to 40dB and regression calculations for the various factors that determines the FWM problem in Optical DWDM system.

Analysis of regression algorithm improves higher optical gain, signal power and provides higher correlation to factors such as output signal power, noise power. The power of eye spectrum characteristic resulting in very good eye opening. It shows from the regression tabulation that increased number of channel deals with higher data rate, and results in high FWM and affects Q-factor for different optical gain values.

From fig.7 eye diagram spectral characteristics, shows an increase in optical gain and improves the power level of DWDM spectrum, leads to higher Q-factor along with dispersion effect. The dispersion effects introduces pulse broadening that directly increases FWM. Other
parameters such as output signal power, noise power, OSNR and power spectral eye characteristics are improved, when the gain of the optical fiber is increased.

Similarly, table 7 shows the effects of RZ modulation format with duty cycle on the various factors for three different channel capacities with R-value and their simulated and predicted regression results.

| Channel & specification | Regression Modeling Equation | $R$ value | Simulated results | Predicted regression results |
|-------------------------|------------------------------|-----------|-------------------|-------------------------------|
| 16-channel & RZ modulation format with duty cycle 0.5 | Output Signal Power : $22.2264 \times (\text{Duty cycle}) - 9.8960$ | 0.9850 | 1.234 | 1.2712 |
| 16-channel & RZ modulation format with duty cycle 0.5 | Noise Power : $25.7706 \times (\text{Duty cycle}) - 60.1908$ | 0.6753 | -50.8069 | 47.3055 |
| 16-channel & RZ modulation format with duty cycle 0.5 | Output Signal Noise Ratio : $3.5441 \times (\text{Duty cycle}) + 50.2941$ | -0.1279 | 52.04172 | 52.06685 |
| 16-channel & RZ modulation format with duty cycle 0.5 | Quality Factor : $14.3359 \times (\text{Duty cycle}) + 30.5241$ | 0.8182 | 37.2133 | 37.69205 |
| 16-channel & RZ modulation format with duty cycle 0.5 | Eye Height : $5.0120 \times 10^{-5} \times (\text{Duty cycle}) + 5.02 \times 10^{-5}$ | 0.9843 | 0.000203 | 0.00010032 |
| 32-channel & RZ modulation format with duty cycle 0.5 | Output Signal Power : $22.2264 \times (\text{Duty cycle}) - 9.8960$ | 0.9850 | 1.228075 | 1.2172 |
| 32-channel & RZ modulation format with duty cycle 0.5 | Noise Power : $25.5318 \times (\text{Duty cycle}) - 59.9653$ | 0.6769 | -50.6358 | -47.1994 |
| 32-channel & RZ modulation format with duty cycle 0.5 | Output Signal Noise Ratio : $3.3044 \times (\text{Duty cycle}) + 50.0174$ | -0.1207 | 51.8639 | 51.7145 |
| 32-channel & RZ modulation format with duty cycle 0.5 | Quality Factor : $11.1442 \times (\text{Duty cycle}) + 30.3554$ | 0.4525 | 36.8455 | 35.9275 |
| 32-channel & RZ modulation format with duty cycle 0.5 | Eye Height : $4.9530 \times 10^{-5} \times (\text{Duty cycle}) + 4.877 \times 10^{-5}$ | 0.9845 | 0.0002 | 0.0001 |
| 64-channel & RZ modulation format with duty cycle 0.25 | Output Signal Power : $22.2254 \times (\text{Duty cycle}) + 5.0989$ | 0.9850 | 11.15812 | 10.65525 |
| 64-channel & RZ modulation format with duty cycle 0.25 | Noise Power : $25.5914 \times (\text{Duty cycle}) - 44.9185$ | 0.6772 | -39.4638 | -38.52065 |
| 64-channel & RZ modulation format with duty cycle 0.25 | Output Signal Noise Ratio : $-3.3658 \times (\text{Duty cycle}) + 50.0174$ | -0.1228 | 50.62189 | 49.17595 |
| 64-channel & RZ modulation format with duty cycle 0.25 | Quality Factor : $-149.3179 \times (\text{Duty cycle}) + 123.1077$ | -0.8344 | 79.1004 | 85.7782 |
| 64-channel & RZ modulation format with duty cycle 0.25 | Eye Height : $0.0154 \times (\text{Duty cycle}) + (-0.0013)$ | 0.9839 | 0.005814 | 0.00255 |

Table 7: Estimated regression equation and their $R$-value for RZ modulation format with duty cycle and their simulated and predicted results.

In this section, modulation format changes from NRZ to RZ format with varying duty cycle from 0.5 to 0.25. Regression values show input and output relationship for system, for defining factors such as BER, output signal power, and eye height characteristics. Noise power shows moderate correlation with RZ format with Duty cycle variations. RZ-modulation format with reduced duty cycle format provides higher BER and reduced Q-factor. This validates that for more number of channels NRZ modulation format provides better results in-terms of Q-factor. Spectral characteristics in eye diagram shows minimum BER, and leads to absolute data transmission, achieving very good Q-factor and increased eye height.

Fig.8 shows the output from spectrum analyser for varying modulation format with different duty cycle from 0.25 to 0.5. The comparative study shows that system design with RZ modulation with low duty cycle and provides better reduction of FWM. It is noticed that increasing duty cycle will lead to higher OSNR and affects Q-factor of the DWDM system, introduces more pulse broadening.

Similarly, table 8 shows the effects of Bit rate on the various factors for three different channel capacities with R-value and their simulated and predicted regression result. In this simulation,
Bit rate is varied from 2.5Gbps to 10Gbps. Increasing bit rate, introduces more BER, which directly causes more dispersion in DWDM system. Non-linearity factors such as noise power and OSNR is enhanced due to occurrence of dispersion in DWDM system, which results in decreased Q-factor. Regression value represents relationship between bit rate and correlation levels to multiple factors such as output signal power, noise power, OSNR, Q-factor and eye characteristic.

| Channel & specification | Regression Modeling Equation | R value | Simulated results | Predicted regression results |
|-------------------------|------------------------------|---------|------------------|----------------------------|
| 16-channel & 10 Gbps data rate | Output Signal Power : -0.4571 × (Bit rate) + 0.4146 | 0.9447 | -3.85899 | -4.1564 |
|                          | Noise Power : -0.2239 × (Bit rate) – 51.3264 | -0.5136 | -54.7055 | -53.5654 |
|                          | Output Signal Noise Ratio : -0.2512 × (Bit rate) + 51.7410 | 0.4243 | 50.84675 | 49.229 |
|                          | Quality Factor: -0.5963 × (Bit rate) +32.2057 | 0.6473 | 28.8337 | 26.2427 |
|                          | Eye Height : -2.35×10^{-5} × (Bit rate) +10.259×10^{-5} | 0.8784 | 8.62×10^{-5} | 7.0×10^{-5} |
| 32-channel & 10 Gbps data rate | Output Signal Power : -0.4837 × (Bit rate) + 0.4482 | 0.9350 | -3.84148 | -4.3888 |
|                          | Noise Power : -0.2175 × (Bit rate) – 51.230 | -0.5344 | -54.4436 | -53.405 |
|                          | Output Signal Noise Ratio : -0.2662 × (Bit rate) + 52.6785 | -0.4506 | 50.6021 | 50.0165 |
|                          | Quality Factor: -0.0878 × (Bit rate) +34.0414 | 0.9834 | 32.4469 | 33.1634 |
|                          | Eye Height : -2.742×10^{-5} × (Bit rate) + 3.28×10^{-5} | 0.9181 | 8.73×10^{-5} | 5.38×10^{-5} |
| 64-channel & 5 Gbps data rate | Output Signal Power : -0.4739 × (Bit rate) + 15353 | 1.0000 | 12.96035 | 12.9835 |
|                          | Noise Power : -0.2240 × (Bit rate) + (-36.1410) | 1.0000 | -37.2259 | -37.261 |
|                          | Output Signal Noise Ratio : -0.2494 × (Bit rate) + 51.4954 | -0.4218 | 50.18625 | 50.2484 |
|                          | Quality Factor: 6.1207 × (Bit rate) + 18.3387 | 0.9975 | 50.8843 | 48.9422 |
|                          | Eye Height : -8.053×10^{-4} × (Bit rate) + 0.0102 | 0.9481 | 0.006434 | 0.0061735 |

Table.8 Estimated regression equations and their R-value for Bit rate with simulated and predicted results

From this analysis, it is observed that noise power and OSNR show lower impact than the other factors such as output signal power, Q-factor and Eye height characteristic. Since higher the number of bits transmitted with respect to more number of channels with good channel spacing, (100GHZ) will reduce noise power and OSNR produces very good spectral characteristic. Fig.9 shows the influence of varying bit rate in a fiber optic DWDM system for the range 2.5Gbps to 10Gbps. From this spectral characteristic, it is proved that higher bit rate will introduces more noise in DWDM system and hence reduces Q-factor. Furthermore decreases eye-height with more pulse broadening.
Similarly, Table 9 shows the effects of core size of an optical fiber on the various factors for three different channel capacities with R-value and their simulated and predicted regression results.

| Channel & specification | Regression Modeling Equation | R value | Simulated results | Predicted regression results |
|-------------------------|-----------------------------|---------|------------------|-----------------------------|
| 16-channel & 80um optical fiber core size | Output Signal Power: -9.92 x 10^-6 (Core size) + 6.3221 | -0.3626 | 6.321816 | 6.32131 |
|                         | Noise Power: 9.7 x 10^-4 (Leaf Core) + (-49.7892) | 0.9005 | -49.79806 | -49.7116 |
|                         | Output Signal Noise Ratio: -9.816 x 10^-4 (Leaf Core) + 56.1204 | -0.8954 | 56.10245 | 56.04182 |
|                         | Quality Factor: -0.01109 x (Leaf Core) + 29.4389 | -0.8961 | 27.5601 | 28.5517 |
|                         | Eye Height: -1.4 x 10^-7 (Leaf Core) + 2.69 x 10^-4 | -0.9037 | 0.000263 | 0.0002572 |
| 32-channel & 160um optical fiber core size | Output Signal Power: 9.48 x 10^-6 (Leaf Core) + 6.3261 | 0.5310 | 6.326529 | 6.327616 |
|                         | Noise Power: -7.3 x 10^-4 (Leaf Core) + (-49.5797) | -0.5668 | -49.6177 | -49.58043 |
|                         | Output Signal Noise Ratio: -7.41 x 10^-4 (Leaf Core) + (55.9058) | 0.5711 | 55.6177 | 55.78724 |
|                         | Quality Factor: -0.01008 x (Leaf Core) + 25.9495 | 0.6693 | 27.0447 | 26.3367 |
|                         | Eye Height: -6.0 x 10^-8 (Leaf Core) + 2.64 x 10^-4 | -0.4743 | 0.000262 | 0.00026344 |
| 64-channel & 80um optical fiber core size | Output Signal Power: -2.3896 x 10^-4 x (Leaf Core) + 11.1811 | -0.9343 | 11.1578 | 11.161982 |
|                         | Noise Power: -8.7 x 10^-4 (Leaf Core) + (-39.4685) | -0.5322 | -39.4511 | -39.5381 |
|                         | Output Signal Noise Ratio: -7.85 x 10^-4 (Leaf Core) + (50.7047) | -0.0625 | 50.60891 | 50.6419 |
|                         | Quality Factor: -0.01034 x (Leaf Core) + 38.832 | -0.9699 | 37.0968 | 38.6048 |
|                         | Eye Height: 2.9332 x 10^-5 x (Leaf Core) + 4.6 x 10^-4 | -0.8640 | 0.002907 | 0.002301 |

Table 9 Estimated regression equations and their R-value for core size of an optical fiber with simulated and predicted results.

Core size of an optical fiber is varied from 80um to 160 um. FWM characteristics are inversely proportional to the core size. From the simulation results, the enlarged core size of an optical fiber degrades FWM. By applying regression analysis to different channel simulation, it shows that increase in the effective core area (A eff) decreases light intensity, inside the optical fiber, degrades the FWM.

Fig.10 gives the spectral characteristics for varying LEAF core of the optic cable from 80um to 160um. Increase in LEAF of an optical fiber shows very good eye opening and achieves a narrow pulse. With good eye–height, maximum Q factor of 27.0447 is achieved for 32-channel DWDM system with 160um core size.
VIII. CONCLUSION

In this work, a comprehensive study of a fiber optic DWDM system, which compensates for nonlinearities such as FWM and high signal distortion with lowers OSNR is presented. Parameter based simulations are run and the results are analysed with regression modelled machine learning algorithm. The machine-learning algorithm establishes correlations among the parameters and provides a strong idea about the major parameters, which influences the FWM. ML based regression modelling is performed towards the optical independent parameters such as channel spacing, bit rate, and the dependent factors such as Max Q-factor, Min BER, noise power, output optical power to meet real time constraints. The proposed R-DWDM provides standard modelling regression equations, which can be directly utilised to increase the efficiency of the output with reduced FWM. The tables from regression modelling indicates the real trade-off between various factors that influence non-linearities in fiber optic R-DWDM system. Low input power (-10dBm) and narrow channel spacing (50GHZ) will provide solution for FWM problem through above equations accommodating more number of channels. However, the parameters are defined according to practical requirements scenarios of data transfer in day-to-day applications. More number of channels with suitable input power and narrow channel spacing is advisable for higher data transmission in real time communication. Optical gain is the level boosting parameter and improves the power level of R-DWDM system, which achieves high Q-factor at the cost of pulse broadening and shows the occurrence of non-linearity. In RZ modulation format with if duty cycle is decreased lower FWM is seen to occur. Increasing the number of channels with higher data rate provides more signal interference with reduced Q-factor. It is mandatory to consider all these parameters to achieve optimized Q-factor, min BER, and required output signal power. Furthermore, the parameters can be extended for more number of dependent and independent variable in various combinations through multiple regression method, as a future scope of this work.

Authors' contributions
V.K and C.A have coordinated the work, V.K, C.A and R.P.G.V have contributed with simulation setup and the proposed modeling design. V.K and R.P.G.V contributed design and implementation. Authors read and approved the final manuscript.

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Competing interests
The authors declare that they have no competing interests.

List of abbreviations
FWM: Four Wave Mixing, OSNR: Output Signal to Noise Ratio, BER: Bit Error Rate, R-DWDM: Regression based Dense Wavelength Division Multiplexing, DWDM: Dense Wavelength Division Multiplexing, XPM: cross phase modulation, SPM: self-phase modulation, WDM : Wavelength Division Multiplexing, TDM: Time Division Multiplexing DCF: Dispersion Compensating Fiber, FBG: Fiber Bragg Grating, NZDSF: Non-zero Dispersion Shifted Fiber, PMD: Polarization Mode Dispersion, AI: Artificial intelligence, ML: Machine Learning, SMF: Single Mode Fiber, LPF: Low Pass Filter, R-value: Regression Value, GHz: Gigahertz (10⁹ hertz).

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Figure 1 Basic simulation setup for DWDM system
Figure 2 Functional schematic of simulation set-up used for parametric analysis.
Figure 3 Process for parametric estimation
Figure 4: R-DWDM Regression model correlation
Varying input power from 10 dB to -10 dB and observing system issues.

| Power Level | Max. Q Factor | Min. BER | Eye Height | Threshold | Decision Inst. |
|-------------|---------------|----------|------------|-----------|----------------|
| -10dBm | 24.2418 | 3.18E-130 | 0.000263448 | 5.31E-05 | 0.535156 |
| 0 dBm | 25.6456 | 1.74E-145 | 0.00263805 | 0.000405274 | 0.535156 |
| 10dBm | 28.4121 | 5.41E-178 | 0.0268805 | 0.00451461 | 0.539063 |

**Fig.5 Influence of Input power in DWDM system**
Fig. 6 Influence of Channel Spacing in DWDM system

| Channel Spacing | Max. Q Factor | Min. BER | Eye Height | Threshold | Decision Inst. |
|-----------------|--------------|----------|------------|-----------|---------------|
| 25GHz           | 2.55866      | 0.004753 | -0.00051   | 0.001521  | 0.804688      |
| 50GHz           | 52.187       | 0        | 0.00283201 | 0.000790958 | 0.5          |
| 100GHz          | 85.5012      | 0        | 0.002926   | 0.000163  | 0.501953      |
Changing the optical gain of 20 dB in to 40 dB And observing the nonlinearities in the wdm system.

|               | 20dB optical gain | 30dB optical gain | 40dB optical gain |
|---------------|-------------------|-------------------|-------------------|
| Max. Q Factor | 33.8541           | 73.9029           | 100.732           |
| Min. BER      | 1.54E-251         | 0                 | 0                 |
| Eye Height    | 8.75E-05          | 0.000920659       | 0.009285          |
| Threshold     | 3.69E-05          | 6.97E-05          | 0.000477          |
| Decision Inst.| 0.478516          | 0.501953          | 0.501953          |

Fig. 7 Influence of optical gain in DWDM system
### Fig. 8 Influence of duty cycle in DWDM system

| Duty Cycle | Max. Q Factor | Min. BER | Eye Height | Threshold | Decision Inst. |
|------------|--------------|----------|------------|-----------|----------------|
| 0.3%       | 93.6647      | 0        | 0.0029291  | 0.000161411 | 0.501953       |
| 0.4%       | 57.2412      | 0        | 0.00489243 | 0.000284715 | 0.501953       |
| 0.5%       | 44.9226      | 0        | 0.0063951  | 0.000435769 | 0.501953       |
Varying bit rate from 2.5 Gbps into 10 Gbps

2.5 Gbps
- Max. Q Factor: 31.2946
- Min. BER: 6.98E-216
- Eye Height: 0.00027081
- Threshold: 4.89E-05
- Decision Inst.: 0.519531

5 Gbps
- Max. Q Factor: 30.356
- Min. BER: 3.07E-198
- Eye Height: 0.000196356
- Threshold: 4.17E-05
- Decision Inst.: 0.316406

10 Gbps
- Max. Q Factor: 28.5337
- Min. BER: 2.18E-179
- Eye Height: 8.62E-05
- Threshold: 3.74E-05
- Decision Inst.: 0.488281

Fig. 9 Influence of bit rate in DWDM system
The effective core size area of optical fibre is changed from 80um into 160um

| Effective Core Size | Max. Q Factor | Min. BER | Eye Height | Threshold | Decision Inst. |
|---------------------|---------------|----------|------------|-----------|---------------|
| 80um                | 24.3447       | 2.59E-131| 0.000264429| 5.21E-05  | 0.533203      |
| 120 um              | 24.8813       | 4.62E-137| 0.000263559| 5.07E-05  | 0.53125       |
| 160um               | 27.0447       | 1.80E-161| 0.000267552| 5.97E-05  | 0.533203      |

**Fig. 10** Influence of effective core size of an optical fiber in DWDM system