Optimization of Different TDM Techniques in DWDM Optical Networks for FWM Suppression

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ABSTRACT

Next-generation optical communication systems demand more capacity, a large number of users, and high data rates this is solved by using Dense Wavelength Division Multiplexing (DWDM) systems with lower interchannel space and high input power. However, increasing power and decreasing space can cause nonlinear effects such as Four Wave Mixing (FWM). Time-Division multiplexing (TDM) can be used to decrease the power of FWM products. In this paper, the effect of TDM combined with DWDM is analysed to reduce FWM. The analysis is carried out and the system is evaluated based on FWM efficiency, Bit Error Rate (BER), Q factor, and received power. Simulations are carried out at 2.5 Gbps, 3.5 Gbps, and 5 Gbps at a transmission length of 100 km. Simulation results show the using 2-TDM, 4-TDM and 8-TDM at different data rates which technique increase system quality. The obtained average FWM efficiency is -68.2, -70.6, and -74.8 respectively. While, 2-TDM, 4-TDM, and 8-TDM provide average Q-factor of 33.9, 19.2, and 12.7 clearly illustrating the surge in system quality. A trade-off between the system's quality and FWM efficiency is done using different data rates.

Keywords: Four-wave mixing; Time division multiplexing; Wavelength division multiplexing; Bit error rate, Dense wavelength division multiplexing.

1. Introduction

In optical communication systems, optical fiber is a medium to send data from source to destination in the form of light using different multiplexing techniques, including WDM and TDM techniques that are used to combine multiple signals before sending signals over a single fiber. WDM is used to transmit multiple signals having different wavelengths over a single optical fiber. In TDM, different signals are transmitted in different time slots (Agrawal, 1995). In TDM, each channel is allocated a unique time slot at the transmitter. However, the overlap between the adjacent channels increases as they propagate through the fiber at different group velocities. Near the zero-dispersion wavelength, the overlap between the adjacent time slots is small, it can also be further minimized by employing dispersion compensation techniques such as dispersion compensating fibers (Okada et al., 1998).

Next-generation optical communication systems require more capacity and a greater number of users. To address the increasing demand for transmitting information over long distances with high capacity, the industry has responded with DWDM technology which is used to send various signals via a single fiber (Habib et al., 2016). In WDM optical networks, to accommodate a greater number of users, channel spacing is reduced to 200 GHz then WDM becomes DWDM (Ullah Manzoor et al., 2020). By using DWDM, some serious nonlinear effects can arise. There are two types of nonlinear effects, e.g., Stimulated Raman Scattering (SRS), Stimulated Brillouin Scattering (SBS) where both are due to light scattering and Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM) and Four Wave Mixing (FWM) which are due to dependence of refractive index on light intensity (Mussot et al., 2006; Sabapathi & Sundaravadivelu, 2011). Nonlinear effects reduce the performance of the system. Fiber is said to be linear if it deals with small input power and is compensated easily but, increasing input power level causes a nonlinear effect in fiber and these effects are very difficult to overcome (Sharma & Kaur, 2018). FWM is the most dominant effect in WDM systems. In FWM, different frequencies interact with each other and generate new frequency components, which can fall into the original spectrum resulting in a broadening of the pulse (Kaur et al., 2010). FWM is one of the serious problems in optical communication which creates power penalties and limits the input power (Reis et al., 2012). Newly produced FWM pulses can reduce the signal-to-noise ratio (SNR) and increase BER. Therefore, in new-generation optical networks FWM is to be avoided (Bi et al., 2014). In a DWDM system, several optical signals are transmitted over a single fiber. To keep the inter-channel spacing as low as possible to accommodate more channels within a specific span. FWM impairment is caused due to the interaction of multiple signals in the fiber leads to the generation of unwanted signals. Moreover, the impact of FWM increases directly with the increase in the number of users in a DWDM configuration (Ali et al., 2021). Parametric analysis of FWM is also carried out in the DWDM system. In this research, valid parameters which lead to the generation and enhancement of FWM, are discussed and simulated. Based on exhaustive sets of obtained results, a detailed analysis has been carried out to reduce the FWM (Ahmed et al., 2014).

In previous research, many optical communication systems have been proposed to mitigate FWM. Some techniques are used, namely; the use of low input power with a high gain amplifier (Ullah Manzoor et al., 2020), a combined Optical Time Division Multiplexing (OTDM), and Wavelength Division Multiplexing (WDM) (Ullah Manzoor et al., 2020).

Another method has been introduced to eliminate FWM, in which alternative circular polarizers are used to change the polarization of input pulses into right- and left-handed polarized pulses before multiplexer resulting in the reduction of FWM (Manzoor et al., 2015).

Somehow, previous research has some limitations. Adding new components can increase the cost of the system and make it more complex. In previous works, only 4-TDM and WDM techniques are used. In this paper, we used the different numbers of channels and different time slicing with the different number of power inputs to investigate which techniques have greater efficiency to reduce FWM while accommodating as many users as possible. The performance of fiber optic communication is evaluated based on Q-factor and BER analysis.

1. FOUR WAVE MIXING

FWM is the most dominant effect in WDM (Šajgalíková et al., 2016). FWM phenomenon occurs due to photons from different waves being generated and destroyed and producing new photons of dissimilar frequencies. FWM products propagate with original pulses and they can also fall into the original spectrum causing crosstalk (Song et al., 1999).

The FWM effect is independent of bit rate, but it is inversely proportional to channel spacing and directly proportional to dispersion (Agrawal, 1995; Morant et al., 2011).

Let λ_i, λ_j and λ_k are three different wavelengths of different channels, then, the fourth wavelength λ_{ijk} generated by FWM is defined as (Chraplyvy, 1990),

$$\lambda_{ijk} = \lambda_i + \lambda_j - \lambda_k \quad (1)$$

where i, j and k can be 1, 2 or 3 and i, j ≠ k.

FWM power is produced by three channels having input power Pi, Pj and Pk following expression (Bogoni & Potì, 2004),

$$P_{ijk} = d_{ijk}\,\gamma\, L_{eff}\, P_i\, P_j\, P_k\, \eta_{ijk}\, e^{-\alpha L} \quad (2)$$

Here, d is a degenerate factor whose value is one for degenerate and two for non-degenerate cases. Leff is the effective length of the fiber, means effective wavelength, is nonlinear effective area, α is the attenuation constant, γ is a nonlinear coefficient which can be defined as (Agrawal, 1995),

$$\gamma = \frac{2\pi\Pi_2}{A_{eff}\lambda} \quad (3)$$

Some of the main disadvantages of FWM are the generation of noise and inter-channel crosstalk which degrades the overall performance of the system. To reduce FWM effects, many technologies are investigated such as a change in channel spacing, using the RZ modulation, Mach-Zehnder modulation techniques, dispersion management technique, Hybrid modulators, etc. (Patnaik & Sahu, 2010; Šajgalíková et al., 2016).

2. Network Architecture

A schematic diagram for TDM/WDM optical communication system is shown in Fig.1. The transmitter side, Tx, of the considered network includes a duobinary precoder, pseudorandom bit sequence (PRBS) generator, continuous wave (CW) laser source, and Mach–Zehnder modulator (MZM). Every CW laser is modulated using an RZ pulse generator by MZM. Continuous wave (CW) laser source has a different range of frequency according to the number of channels used and input power range from -7dBm to 7dBm. Pseudorandom bit sequence (PRBS) generator generates contains bit rates from 2.5Ghz to 5Ghz. MZM is a modulator used to modulate random binary bit with a CW laser and convert it into an optical signal. it has extinction ration 40dB and symmetry factor is -1.The MZM is connected to a power splitter having ports equal to the number of time divisions. Every port is connected to a time delayer of 1/ (bit rate × i/n) seconds, respectively, where i = port number (1,2,3…) and n = total number of time divisions. After time delayers, all ports are connected to a power combiner which is used to combine the power of all the TDM channels. Then power combiner is connected to a multiplexer (MUX). The MUX is further connected to a 100 km single mode optical fiber (SMF) having a dispersion of 16.75 ps/nm/km and a dispersion slope of 0.075 ps/nm^2/km with attenuation of 0.2 dB/km. The SMF is connected to a 21 km DCF (dispersion compensating fiber) having -80 ps/nm/km dispersion and -0.358 ps/nm^2/km dispersion slope with an attenuation of 0.2 dB/km. The DCF is added so that the total residual dispersion is equal to zero. The DCF is used to improve the transmission performance which is affected by dispersion. Then, the DCF is followed by a 20 dB optical amplifier. On the receiver side, the demultiplexer (DEMUX) is connected to a power splitter connected to time delayers. These time delayers are further connected to the receiver with a cut-off frequency of 0.75×bit rate. PIN photodetector is used that convert light into an electrical voltage. It has an ionization ratio of 0.9A/W, dark current is 10 nA with 0 insertion loss and 1e-022W/Hz thermal noise For analyzing and visualizing, the optical receiver is further connected to an eye diagram analyzer, and optical power meter.

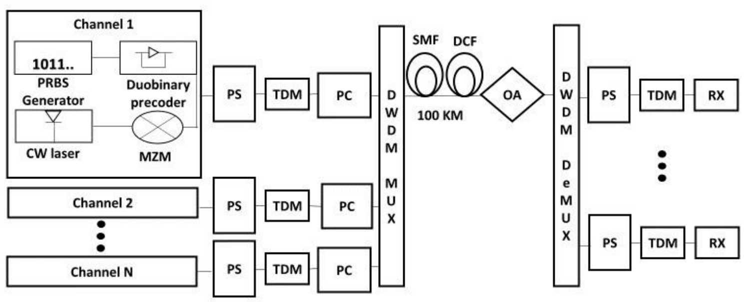

Fig.1 TDM/WDM optical communication system.

To understand the effect of time divisions on FWM products, different time divisions, from zero to eight, are considered. In all the considered time divisions, the numbers of users are kept constant. In a 2-TDM system, 32 channels and 2-time delayers can accommodate (2×32) 64 users. In 4the -TDM system, 16 channels and 4-time delayers are used to accommodate 64 users. Similarly, 8-TDM system 8with channels and 8-time delayers are used to accommodate (8×8) 64 users.

3. Simulation Setup

➢ **<u>0-TDM system</u>**

The schematic diagram for 0-TDM/WDM transmitter in the considered network from Fig. 1 is shown in Fig.2 in an optical fiber-based communication system. The proposed transmitter system consists of 64 channels used as a transmitter space at 100 GHz, having input power from -5 dBm to 5 dBm. The channel frequencies are from 193.1 THz to 199.4 THz. Every CW laser is modulated using a RZ pulse generator by MZM. The MZM is connected to a multiplexer (MUX). Here the system capacity for 2.5 Gbps (64 channel×2.5 Gbps) is 160 Gbps, for 3.5 Gbps (64channel×3.5 Gbps) is 224 Gbps and for 5 Gbps (64 channel×5 Gbps) is 320 Gbps.

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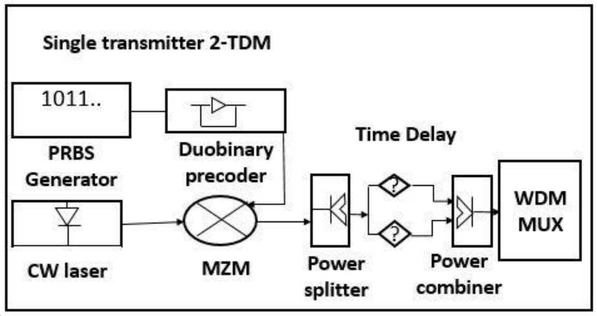


Fig.2 Single transmitter (0-TDM)

The simulation results of the 0-TDM/WDM standard system are displayed in Figs.3. In Fig.3(a) shows the spectrum analysis of a single transmitter of 0-TDM before SMF. There are 64 channels having a power of 0 dBm, the data rate of 2.5 GHz, and no FWM products. Fig.3(b), shows the standard system before DEMUX. The spectrum contains original pulses at 0 dBm and FWM products at −67 dBm and a Q-factor of 63.5 which is evaluated using an eye diagram.

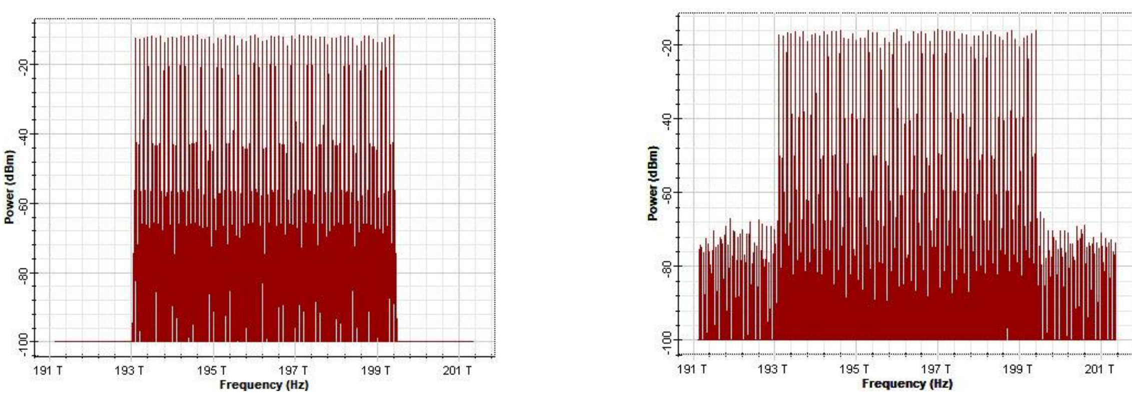


Fig.3 (a) Launched signal for no TDM. (b) Spectrum before DEMUX containing original pulses and FWM products

- **2-TDM system**

Figure. 4 shows the schematic diagram for 2-TDM/WDM system. The proposed transmitter system consists of 32 channels used as a transmitter space at 200 GHz. The channel frequencies are from 193.1 THz to 199.3 THz. In this simulation, the MZM is connected to a power splitter of two ports, every port is connected to a time delayer of (1/ (bit rate × i/2)) s where i = 0,1. After the time delayer, a power combiner is used to combine all the ports. Then, the power combiner is connected to WDM (MUX). On the receiver side, the DEMUX is connected to a power splitter connected to 2-time delayers. The rest of the standard system is kept the same as before. Here the system capacity for 2.5 Gbps (32 channel×2.5 Gbps) is 80 Gbps, for 3.5 Gbps (32 channel×3.5 Gbps) is 112 Gbps and for 5 Gbps (32 channel×5 Gbps) is 160 Gbps. Each channel is divided into 2 parts using OTDM. If two users are adjusted on a single frequency, then 64 users can be accommodated in the entire system and system capacity is increased using 2-OTDM is (32 channels×2) 64. The increased system capacity (64×2.5 Gbps) is 160 Gbps, (64×3.5 Gbps) is 224 Gbps, and (64×5 Gbps) is 320 Gbps.

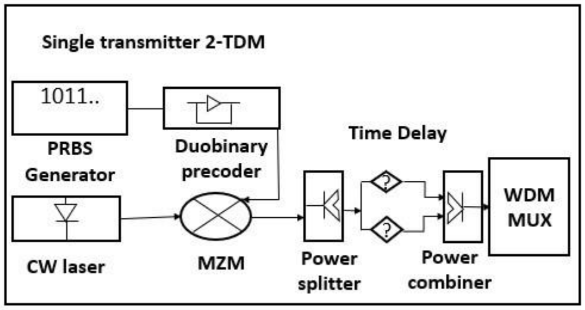


Fig.4 Single transmitter (2-TDM).

- **<u>4-TDM system</u>**

Figure.5 shows the schematic diagram for 4-TDM/WDM system. The proposed transmitter system consists of 16-channels used as a transmitter space at 200 GHz. The channel frequencies are from 193.1 THz to 196.1 THz. In this simulation, the power splitter has 4 ports, every port is connected to a time delayer of (1/ (bit rate × i/4)) s where i = 0,1,2,3. The rest of the standard system is kept the same as before. Here the system capacity for 2.5 Gbps (16 channel×2.5 Gbps) is 40 Gbps, for 3.5 Gbps (16 channel×3.5 Gbps) is 56 Gbps and for 5 Gbps (16 channel×5 Gbps) is 80 Gbps. Each channel is divided into 4 parts using OTDM. If two users are adjusted on a single frequency, then, 64 users can be accommodated in the entire system and system capacity is increased using 4-OTDM IS (16 channels×4) 64. The increased system capacity (64×2.5 Gbps) is 160Gbps, (64×3.5 Gbps) is 224Gbps, and (64×5 Gbps) is 320 Gbps.

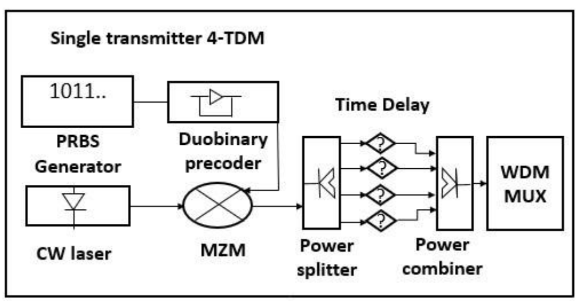


Fig.5 Single transmitter (4-TDM).

- **<u>8-TDM system</u>**

Figure.6 shows the schematic diagram for 8-TDM/WDM system. The proposed transmitter system has an 8-channel configuration. The channel frequencies range between 193.1 THz and 194.5 THz. The MZM is connected to a power splitter of 8 ports in this simulation, with each port connected to a time delayer of (1/ (bit rate × i/8)) s, where i = 0,1,2,3,4,5,6,7. The rest of the standard system remains the same. The system capacity here is 20 Gbps for 2.5 Gbps (8 channel × 2.5 Gbps), 28 Gbps for 3.5 Gbps (8 channel3.5 Gbps), and 40 Gbps for 5 Gbps (8 channel5 Gbps). Each channel is divided into 8 parts using OTDM. If two users are adjusted on a single frequency, then 64 users can be accommodated in the entire system and system capacity is increased using 8-OTDM IS

(8×8) 64. The increased system capacity (64×2.5 Gbps) is 160 Gbps, (64×3.5 Gbps) is 224 Gbps, and (64×5 Gbps) is 320 Gbps.

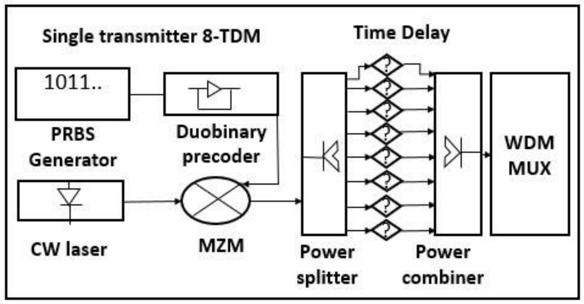
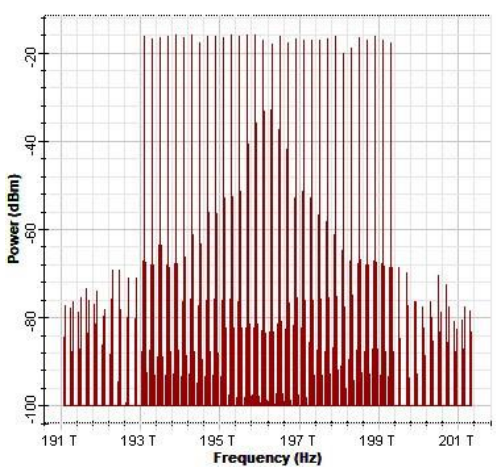


Fig. 6 Single transmitter (8-TDM).

4. Comparative Analysis and Discuss the Comparison:

In this simulation, the 2-TDM technique is used having 32 channels. In Fig.7(a), the spectrum contains original pulses at 0 dBm and FWM products at -68 dBm having an average Q-factor of 33 evaluated using an eye diagram. In Fig.7(b), 2-TDM is replaced with 4-TDM having 16 channels. The remaining system parameters are kept as a standard system. Figure. 7(b) shows the spectrum of the 4-TDM system. Compared with the 2-TDM system (presented in Fig. 7(a)) an increase in the power of FWM products is noticed from −67 to −70 dBm and the Q-factor has decreased from 33 to 19.2. Next, the 8-TDM technique is used having 8 channels. Figure. 7(c) shows the spectrum analysis of the 8-TDM system before DEMUX. Compared with the 4-TDM system (presented in Fig. 7(a)) an increase in the power of FWM products is noticed from −70 to −74 dBm and Q-factor has decreased from 19.2 to 12.7.



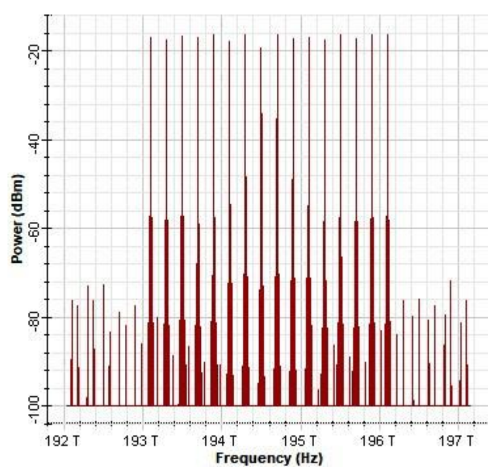
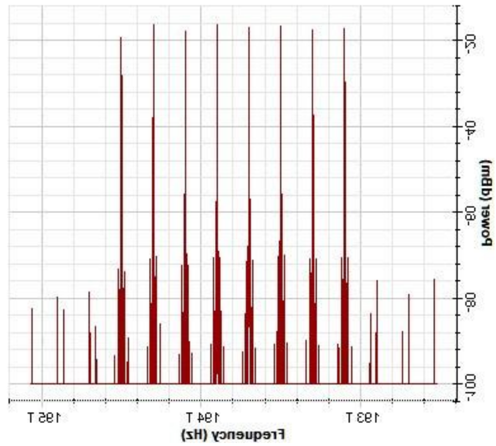


Fig.7 (a) Spectrum before DEMUX when the 2-TDM technique is used (b) Spectrum before DEMUX when the 4-TDM technique is used



(c) Spectrum before DEMUX when the 8-TDM technique is used

The simulation results of the 2/4/8-TDM system are shown in figs. 8-12. These graphs show the average Q-factor, OSNR, received power and FWM power. In this system, 0-TDM, 2-TDM, 4-TDM, and 8-TDM techniques are compared to check the best TDM technique to reduce FWM. The transmission performance of the proposed model is evaluated on basis of average OSNR and Q-factor using different values of optical power and data rates shown in the graph. The transmission performance of the proposed model in terms of Q-factor against different time division techniques has an average input power from -5 dBm to 5 dBm and a data rate of 2.5 GHz. Figure. 8 shows that 2-TDM and 0-TDM techniques' performance is better than 4-TDM and 8-TDM but, without TDM the system suffers an interference effect and has a distorted signal as compared to TDM techniques. Comparing the 2-TDM technique with 4-TDM and 8-TDM, its performance is better than other techniques. The 8-TDM is performing worse. it simply shows that 2-TDM and 4-TDM perform better with the proposed model. The data rate is increased from 2.5 GHz to 3.5 GHz to check the performance of the proposed model at a 100 km length of optical fiber. Figure. 8 shows the Q-factor of the proposed model for different TDM techniques. Its shows that the Q-factor decreases with an increase in data rate. The Q-factor is reduced from 33.9 to 16 for 2-TDM and 19.2 to 8.7 for 4-TDM with increasing the data rate. For 8-TDM, the signal is attenuated and distorted. So, the Q-factor is 0. Now, further increasing the data rate from 3.5 GHz to 5 GHz. Fig. 8 shows that the Q-factor is reduced from 33.9 to 16.2 for 2-TDM and 19.2 to 10.19 for 4-TDM with an increase in data rate.

The transmission performance in terms of FWM power against different TDM techniques is displayed in fig. 9 which shows the efficiency reduces from -64.4 dB to -83.0 when using 2-TDM instead of 4-TDM. Again, increasing the data rate to 3.5 GHz and 5 GHz, the graph shows an increase in FWM power with the increase in data rate. For 8-TDM, the FWM power is approximately -100 dBm.

Figure.10 displays the received power of the proposed model. Analyzing the received output power reveals that 2-TDM has higher received power than 4-TDM and 8-TDM. The output power decreases from 15.3 to -17.8 for 2-TDM and -19.3 to -22 with the increase in data rate. Figure.11 shows the OSNR of the proposed model. It shows that 2-TDM and 4-TDM have greater OSNR than 8-TDM and an increase in data rate leads to a decrease the OSNR.

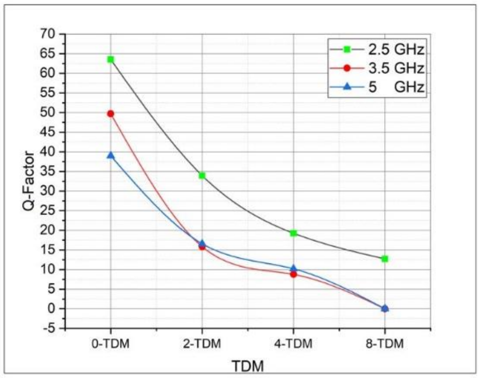


Fig.8 Q-factor of different TDM techniques at different data rates

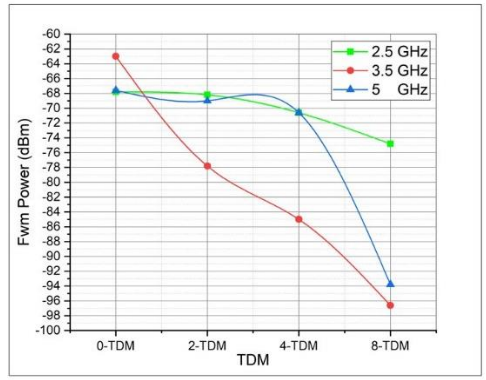


Fig.9 FWM Power of different TDM techniques at different data rates

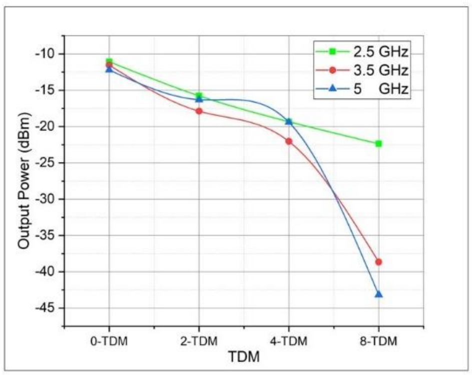


Fig.10 Rx Power of different TDM techniques at different data rates

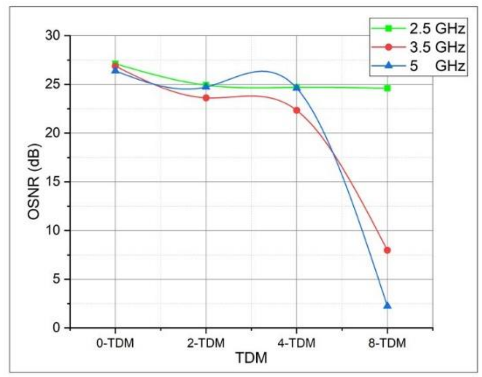
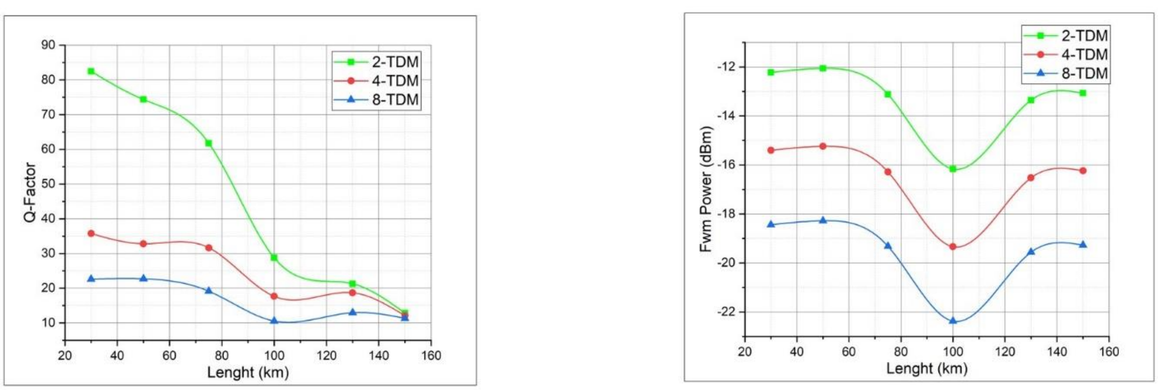


Fig.11 OSNR of different TDM techniques at different data rates

In addition, the TDM technique is analyzed for different lengths from 30 km to 150 km. The FWM power and Q-factor are calculated against different lengths to check the performance of the proposed model. Figure.12 (a) shows the Q-factor versus different lengths at 0 dBm input power. It shows that the Q-factor reduces with the increase in length. At a length 150 km the Q-factor of 2/4/8-TDM is approximately equal. The Q-factor of 2-TDM decreases more rapidly than the other two techniques. Figure.12 (b) shows the FWM power against length, where the 8-TDM has higher FWM power than 4-TDM and 8-TDM.



(a) **(b)**

Fig. 12(a) Q-factor against the different lengths (b) FWM Power against the different length

The result of BER is shown in Table.1 against different TDM techniques. BER is evaluated using an eye diagram for different TDM techniques. It shows that the BER of 8-TDM for 2.5 GHz is higher as compared to 0/2/4-TDM. The 0-TDM has low BER, but, it uses a large number of channels which increases cost and channel re-useability. An optical communication system is required to transmit a large amount of data and an increasing number of users with a smaller number of channels. According to this, 2-TDM and 4-TDM have great performance, with increasing the data rate to 3.5 GHz and 5 GHz. It shows that BER for 3.5 GHz increases from 1.01E-45 to 7.90E-12 for 2-TDM and 8.18E-12 to 1.76E-03 for 4-TDM and BER for 5 GHz increases from 1.01E-45 to 1.18E-15 for 2-TDM and 8.18E-12 to 4.54E-07 for 4-TDM. The BER of 8-TDM is 1 because the increase in data will increase the error and the signal is completely distorted. It is concluded that increased data rate increases BER. Now, analyze the system by comparison shown in Table.2.

Table.1 BER of different TDM techniques at different data rates

TDM Technique	BER	BER	BER
Bit Rate	**2.5 GHz**	**3.5 GHz**	**5 GHz**
0-TDM	0	0	4.40E-77
2-TDM	1.006E-45	1.18E-15	7.90E-12
4-TDM	8.18E-12	4.54E-07	1.76E-03
8-TDM	4.18E-5	1	1

Table.2 Comparison between different techniques

Bit Rate/ Technique	Avg. Received Power (dBm)	Avg. Q-factor	Avg. BER	Avg. Fwm Power (dBm)	FWM Efficiency
2.5GHz					
2-TDM	-15.75	33.93	1.01E-45	-68.2	-83.056
4-TDM	-19.32	19.25	8.18E-12	-70.6	-64.494
8-TDM	-22.37	12.71	4.18E-05	-74.8	-53.244
3.5GHz					
2-TDM	-17.878	15.851	7.90E-12	-77.8	-81.513
4-TDM	-22.036	8.778	1.76E-03	-85	-80.088
8-TDM	-38.65	0	1	-96.6	-85.436
5GHz					
2-TDM	-16.3	16.59	1.18E-15	-69	-78.06
4-TDM	-19.4	10.19	4.54E-07	-70.6	-64.07
8-TDM	-43.18	0	1	-93.8	-67.13

5. Conclusion

Optical fiber communication requires a reliable and efficient system. Our goal is to optimize the system by analyzing which TDM techniques have more capacity, the least BER, and use a greater number of users. 2-TDM, 4-TDM and 8-TDM techniques are investigated and then compared. All the techniques have the same number of users and different numbers of channels. By comparing these techniques, 2-TDM has a higher Q-factor and lower BER as compared to 4-TDM and 8-TDM. The 8-TDM has the worst performance of all. Based on obtained results, all techniques have the same number of users, it is concluded that the 2-TDM has better performance than other techniques. It fulfils our requirement, it has high performance, more capacity and uses a greater number of users.

Statements and Declarations

Ethical approval

Not Applicable

Competing interests

The authors declare that they have no competing interests

Authors' contributions

A.K., H.U.M., H.A.H., M.H.A. have directly participated in the planning, execution, and analysis of this study. A.K. drafted the manuscript. All authors have read and approved the final version of the manuscript.

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Availability of data and materials

The data used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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