International Journal of Engineering Trends and Technology
ISSN: 2231 – 5381 / https://doi.org/10.14445/22315381/IJETT-V71I1P205

Volume 71 Issue 1, 41-52, January 2023

Original Article

Design and Analysis of 8-Channel WDM-RoF Using the C and L Band for 5G and Beyond Applications

Deepak Jain[1], Brijesh Iyer[2]

[1,2]*Department of Electronics & Telecommunication Engineering, Dr. Babasaheb Ambedkar Technological University, Lonere-India*

[1]*Corresponding Author : ddsj2005@gmail.com*

Received: 07 September 2022 Revised: 09 December 2022 Accepted: 26 December 2022 Published: 24 January 2023

Abstract *- The present article demonstrated an 8-channel c and l band WDM system using radio over fiber. The radio over fiber is a boon for the modern era of 5G and beyond communication. Many communication applications use only the C band, which is highly congested. The proposed method makes use of both the C (1530-1565 nm) and L (1565-1625 nm) bands. C and L bands provide low fibre attenuation and are thus preferred for Radio over Fiber communication. The presented scheme has a data rate of 8x10 Gbit/s. The laser pumping is comparatively low at the transmitter, only -5 dBm. Optisystem 19 was used to simulate this system. This system is evaluated using parameters such as BER, SNR, OSNR, quality factor, and eye diagram. The design works best up to a fiber length of 60 km. This approach makes use of SMF fiber with a wavelength of 1550 nm. The article reports Q factor and BER of 7.70, 6.74, 6.99, 7.91, 6.31, 5.42, 5.98, 6.08, and 6.62e-15, 7.24e-12, 1.23e-12, 1.22e-15, 1.38e-10, 2.94e-08, 1.08e-09, 5.93e-10 at 60 km of optical fiber.*

Keywords *- BER- Bit Error Rate, LiNb MZM- Lithium Niobate Mach–Zehnder Modulator, MZM-Mach–Zehnder Modulator, NRZ- Non-Return to Zero, PRBS-Pseudo Random Binary Sequence, RoF-Radio over Fiber, SMF-Single-Mode Fiber, WDM-Wavelength Division Multiplexing.*

1. Introduction

Optical fibre communication and wi-fi communication have become an essential part of modern life in the 5G era. We use many electronic devices that have wi-fi capabilities in our daily lives. As a result, wireless communication is becoming increasingly important for humans. Massive bandwidth and low transmission power are required for 5G and future applications. This requirement is easily met by the enormous bandwidth of optical fiber [1].

Two types of optical amplifiers are often used to amplify an optical signal: Optical Fiber amplifiers (OFA) and Semiconductor Optical amplifiers (SOA). OFA is further subdivided into EDFA, YDFA, PDFA, and Raman amplifiers. It has been discovered that the Yb-doped fiber amplifier exhibits strong in-band ASE (amplified spontaneous emission) at 980 and 1030 nm. A theoretical and practical study was performed to suppress the in-band ASE and the 1030 nm ASE [2]. DWDM (Dense Wave Division Multiplexing) is an important Silicon photonics transceiver for wireless communication. An 8-channel DWDM transceiver with a data rate of 8x14 Gbps has been designed. This system transmitted data over 10 km of optical fiber with bit error rates between 8e-4 and 1e-5 [3].
In conjunction with an RoF system, WDM converts RF (Radio Frequency) signals into optical signals transmitted over optical fiber. It is best suited for 4G wireless communication system applications. To meet the increasing bandwidth and data rate demands, WDM can be combined with PON. The WDM RoF system is built with PON (Passive Optical Network) technology based on FBG (Fiber Bragg Grating) [4, 5].

In communication via multimode optical fiber, the degradation of an optical signal is caused by chromatic and multimode dispersion. It has been realized that optical frequency multiplication (OFM) can be used as an RoF technique to overcome dispersion. High-capacity RF data can be optically routed and transmitted over multimode fiber. In multimode fiber, optical frequency multiplication was predominantly used. Subcarrier multiplexing and orthogonal frequency division multiplexing were utilized to achieve OFM [19].

The bandwidth of optical fibers is enormous. To effectively use this bandwidth, an eight-channel WDM system was developed [7]. In the C and L bands, erbium-doped fiber amplifiers prefer for long-distance optical communication. EDFA has a high gain and a low noise insertion. EDFA was used as a repeater amplifier in the WDM system design, and minimal BER was achieved [8, 9]. The system can be expanded to become a 16-channel, 32-channel, or 64-channel WDM system [10, 11].

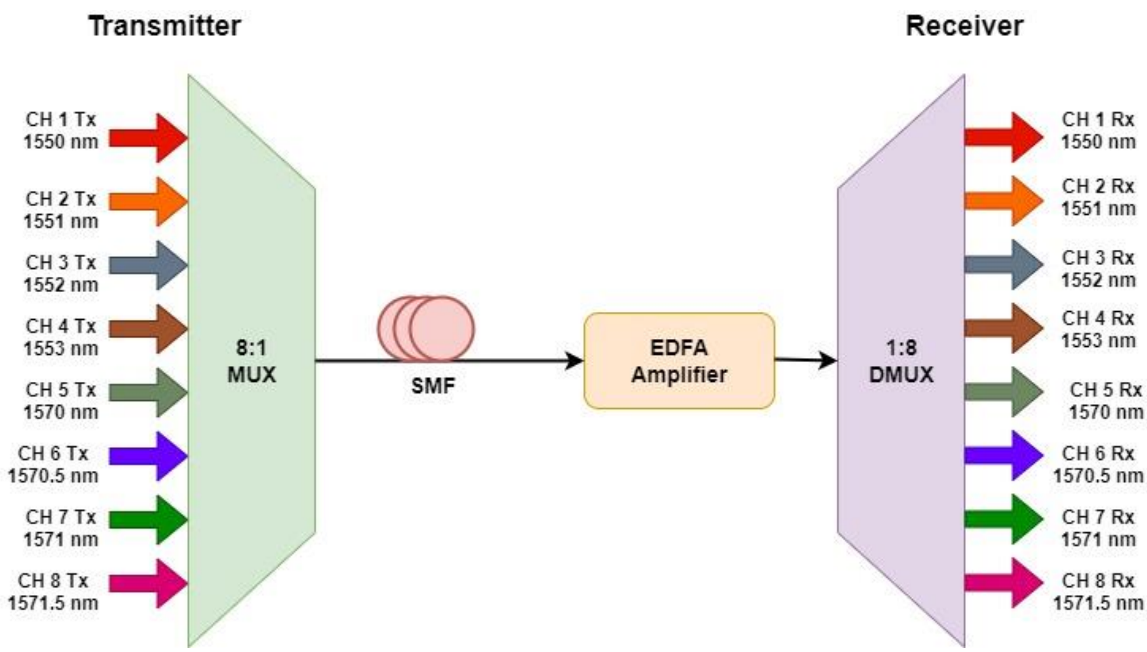


Fig. 1 Generalized block schematic of the proposed method

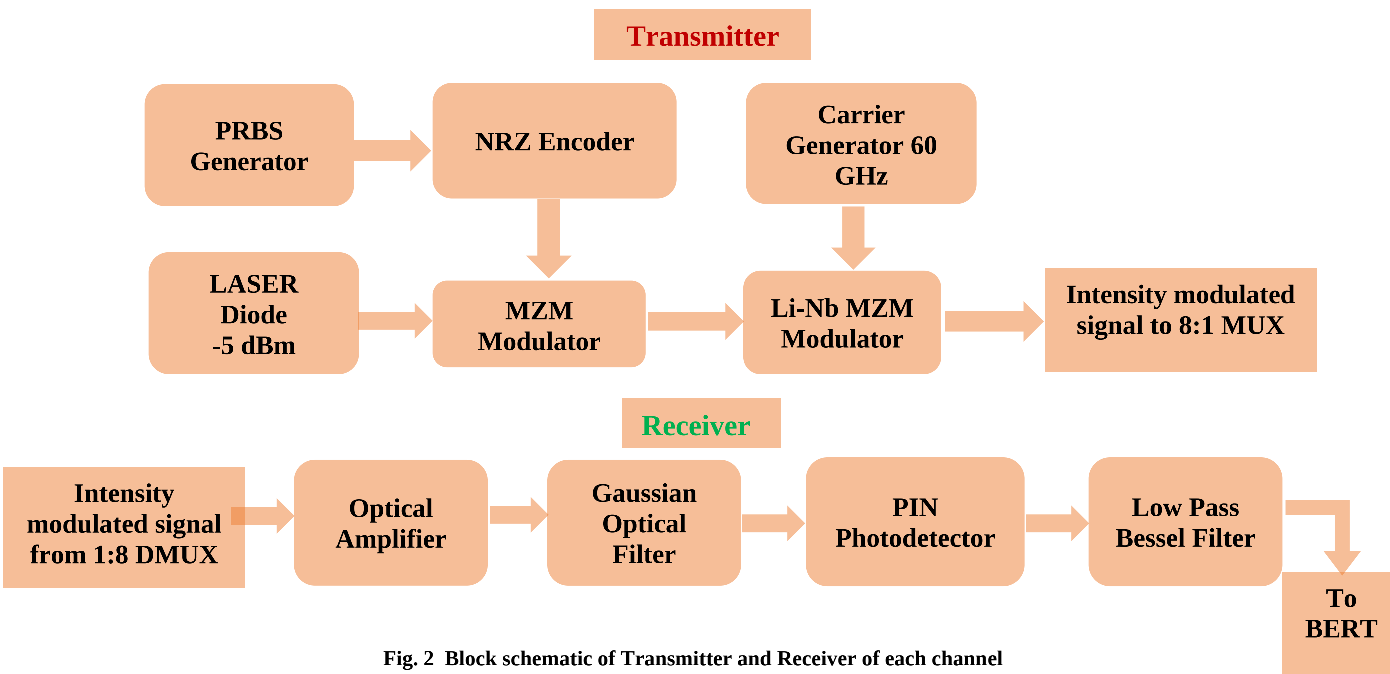


Fig. 2 Block schematic of Transmitter and Receiver of each channel

Four-wave mixing (FWM) is a severe issue in DWDM that causes optical signal attenuation. Third-order optical nonlinearity causes the nonlinear effect of four-wave mixing. It occurs when two or more optical signals with different wavelengths propagate through a single optical fiber, resulting in the generation of a fourth wavelength optical signal. FWM limits the channel density and data rate in a WDM system. A DWDM hybrid modulation technique has been developed to minimize FWM [12-14]. Table 1 summarises the literature and compares various Radio over Fiber WDM systems.

Referring to and studying various journals, it was discovered that almost all WDM Radio over Fiber methods use only the low attenuation C band. However, optical fiber communication has another low attenuation L band. It is the primary area of research for high-speed WDM systems. As a result, in this article, the use of C and L bands for the higher generation high data rate WDM-RoF system has been suggested to meet the demand for higher bandwidth and lower transmission power.

Table 1. The State of the art of literature and comparison of Radio over Fiber in WDM systems

Ref no	No of channels	Data rate (Gbps)	Optical bands	BER	Type of amplifier	Laser pumping (dBm)	Application	Fiber link (km)
[3]	08	8x14	C	e-5 to e-7	SOA	0 to -4	To minimize BER in DWDM	10
[4]	04	4x2	C	e-9	Reflective semiconductor optical amplifier (RSOA)	10	Wireless, broadband communication	20
[5]	02	1x2	C	2.78e-72	Optical amplifier	0	RF wireless and Optical fiber communication	40
[19]	10	10x0.21	-	-	SOA	-	To have a minimum error magnitude (EVM) of less than 6% in high capacity RoF network	4.4
[7]	8	2.5x8	C	0	EDFA	10	In WDM Radio over Fiber communication with zero BER	90
[8]	8	2.5X8	C	e-7 to e-10	EDFA	0	High-capacity wireless communication	100
[9]	8	-	C	e-23 to e-302	EDFA	-28	It can be used in 8-channel WDM with very low BER	30
[10]	16	16x10	C	e-267	EDFA	-	It can be used for the DWDM system.	80
[12]	8	2.5X8	C	e-14	Optical amplifier	-10	In a high-capacity DWDM system	100
[13]	4	1x4	C	0.00027	EDFA	-15 to 15	It is used in the WDM-RoF system	60
[14]	4	4x10	C	e-8 to e-9	Optical amplifier	0	It is used in the WDM-RoF system for long-distance communication	70
[15]	4	4x3	C	2.6e-30	EDFA	5	It can be used in RoF communication	130
[17]	8	8x12	C	e-58	Optical amplifier	0	For RoF communication	120

The rest of the paper is organized as the first section introduces the proposed system and conducts a literature review. Section 2 - This section describes the experimental setup and blocks schematic for the proposed system, which operates at an 80 Gbps data rate. Section 3 describes the experimental verification of the posed method along with the results and discussions by varying the fiber length from 30 to 70 km. Section 4 concludes the paper with a discussion of the future scope.

2. Experimental Setup of the Proposed Model

Figure 1 depicts a schematic diagram of the eight-channel WDM RoF system. It is divided into three parts, as shown below: transmitter, channel, and receiver. Optisystem 19 was used to run the simulation.

Many WDM RoF systems are only designed for the C band, which is now extremely crowded. The current scheme employs both the low attenuation bands C (1530-1565 nm) and L (1530-1565 nm) (1565-1625 nm). The eight channels in the proposed simulation are as follows: the first four are from the C band (channels 1-4), and the remaining four are from the L band (channels 5-8). The wavelengths of channels 1–4 in the C band are 1550 nm, 1551 nm, 1552 nm, and 1553 nm, respectively. L band channels 5 to 8 have wavelengths of 1570 - 1571—5 nm in a 0.5 nm span.

Each transmitter, as shown in Figure 2, contains a PRBS generator, NRZ encoder, laser diode, MZM modulators, and; a carrier generator. A PRBS generator produces pseudorandom binary sequences with a data rate of 10 Gbps since NRZ encoding performs better over longer distances. As a result, the pseudorandom binary sequence encodes using the NRZ encoder. A laser diode is pumped at a very low power of -5 dBm. In the MZM modulator, the laser beam from the laser diode is light-modulated using the encoded binary sequence. The optically modulated signal is further modulated in the Li-Nb MZM modulator with a sinusoidal carrier of 60 GHz. The 8:1 multiplexer then receives the light intensity modulated signal. Using wavelength division multiplexing, the multiplexer multiplexes RoF signals from different channels. The WDM RoF on SMF operated at a 1550 nm reference wavelength.

The optical signal is demultiplexed by the 1:8 demultiplexer and then applied to the appropriate receiver.

Figure 2 illustrates the receiver section, including an optical amplifier, a Gaussian optical filter, a PIN photodetector, and a low-pass filter. The intensity-modulated signal is applied to the optical amplifier to boost the signal. The amplified optical signal was subjected to a Gaussian bandpass filter to remove noise. The noise-free optical signal is applied to a photodetector, which converts the optical signal to an electric signal. The RF electrical signal is filtered using a low-pass Bessel filter. A BER analyzer is used to evaluate the received electrical signal. The variation in Q factor, BER, SNR, and OSNR is investigated by varying the fiber length. Table 2 shows the essential design parameters for simulating the proposed method [14].

Table 2. Simulation parameters for the present approach

Design Parameters	Value
Single Mode Fiber (SMF)	
Reference Wavelength of SMF	1550 (nm)
SMF attenuation	0.2 (dB/km)
Dispersion	16.75 (ps/nm/km)
Effective area	80 (µm2)
Variation in fiber length	30 - 70 (km)
Slope of dispersion	0.075 (ps/nm2/km)
Laser Diode	
Laser power	-5 (dBm)
Line width	10 (MHz)
Initial phase	0 (deg)
EDFA Amplifier	
Core radius	2.2 (µm)
Er doping radius	2.2 (µm)
Numerical aperture	(0.24)
Length	5 (m)
Forward pump length	980 (nm)
Forward pump power	40 (dBm)
MZM modulator	
Extinction ratio	30 (dB)
Insertion Loss	5 (dB)
Chirp factor	0.5

3. Results and Discussion

The presented system was modeled using the Optisystem 19 simulation software. Laser power is an important consideration when developing WDM radio over fiber systems. The experimental design runs at a low laser power of -5 dBm to meet the goal of low power consumption. The reference wavelength of single-mode optical fiber was kept at 1550 nm. Table 2 lists the simulation parameters in optisystem 19 for the designed system. The recommended system's results were investigated using BER, an eye diagram, a quality factor, an output signal-to-noise ratio, and an optical signal-to-noise ratio. The quality factor of the 8-channel Radio over Fiber system is in Table 3.

The better the system performance, the significantly greater the quality factor; conversely, the poorer the system performance, the lower the quality factor [15-16]. The Q factors for channels 1–8 at 30 km of optical fiber length were 10.24, 8.71, 8.62, 9.05, 6.21, 5.96, 5.36, and 6.88, respectively. 7.70, 6.74, 6.99, 7.91, 6.31, 5.42, 5.98, and 6.08 are the quality factors that have decreased.

The Q factors for channels 1–8 at 30 km of optical fiber length were 10.24, 8.71, 8.62, 9.05, 6.21, 5.96, 5.36, and 6.88, respectively. 7.70, 6.74, 6.99, 7.91, 6.31, 5.42, 5.98, and 6.08 are the quality factors that have decreased. The minimum quality factor required for good signal reception is 6. The proposed system achieves the desirable quality factor even at 60 km of fiber length. The decrease in quality factor from 30 km to 60 km is due to the empirical fact that as fiber length increases, so do attenuation, dispersion, and propagation losses. Table 3 also shows that at 70 km, the C band channels provide a good response because they are closer to the fiber's reference wavelength [17]. On the other hand, the L band four channels do not deliver the desired response. As a result, the proposed method works best up to 60 km. Bit error rate (BER), in addition to quality factor, is a defining parameter for describing the overall performance of a Radio over Fiber system. Table 4 depicts the bit error rate of the proposed approach. The bit error rate is described as the ratio of the number of incorrect bits received to the total bits transmitted [15].

Table 3. Maximum Quality factor

Fiber length in km	Ch-1	Ch-2	Ch-3	Ch-4	Ch-5	Ch-6	Ch-7	Ch-8
30	10.24	8.71	8.62	9.05	6.21	5.96	5.36	6.88
40	8.09	7.04	7.88	8.71	6.51	5.75	6.19	6.85
50	7.93	7.17	7.61	8.47	7.15	5.87	6.52	6.67
60	7.70	6.74	6.99	7.91	6.31	5.42	5.98	6.08
70	6.80	6.16	6.37	7.05	1.73	1.69	1.90	1.65

Table 4. Bit Error Rate of the proposed method

Fiber length in km	Ch-1	Ch-2	Ch-3	Ch-4	Ch-5	Ch-6	Ch-7	Ch-8
30	5.83e-25	1.26e-18	2.80e-18	6.23e-20	2.52e-10	1.15e-09	3.93e-08	2.78e-12
40	2.47e-16	7.75e-13	1.34e-15	1.29e-18	3.41e-11	4.04e-09	2.80e-11	3.55e-12
50	9.94e-16	3.27e-13	1.22e-14	1.12e-17	4.14e-13	6.74e-09	3.32e-10	1.27e-11
60	6.62e-15	7.24e-12	1.23e-12	1.22e-15	1.38e-10	2.94e-08	1.08e-09	5.93e-10
70	5.14e-12	3.47e-10	9.13e-11	8.91e-13	0.032	0.033	0.02	0.037

Table 5. Output OSNR (dB)

Fiber length in km	Ch-1	Ch-2	Ch-3	Ch-4	Ch-5	Ch-6	Ch-7	Ch-8
30	54.21	54.35	45.01	32.67	31.51	30.68	29.47	28.28
40	53.01	53.13	43.63	31.92	29.97	29.29	28.18	27.46
50	52.82	52.90	43.30	31.44	29.29	28.32	27.47	26.19
60	52.17	51.17	42.08	30.78	27.78	26.69	25.86	25.50
70	51.39	49.71	40.54	30.70	25.89	25.17	24.75	24.07

Table 6. Output SNR (dB)

Fiber length in km)	Ch-1	Ch-2	Ch-3	Ch-4	Ch-5	Ch-6	Ch-7	Ch-8
30	58.19	58.33	48.99	36.65	35.49	34.66	33.45	32.26
40	56.99	57.11	47.61	35.90	33.95	33.27	32.16	31.44
50	56.80	56.88	47.28	35.42	33.27	32.30	31.45	30.17
60	56.15	55.15	46.06	34.76	31.76	30.66	29.84	29.48
70	55.37	53.69	44.51	34.68	29.87	29.15	28.73	28.05

At 30 km length, the BER of the system under investigation was 5.83e-25, 1.26e-18, 2.80e-18, 6.23e-20, 2.52e-10, 1.15e-09, 3.93e-08, and 2.78e-12 for the 8 channels, respectively. However, at 60 km of fiber, the bit error rate increases to 6.62e-15, 7.24e-12, 1.23e-12, 1.22e-15, 1.38e-10, 2.94e-08, 1.08e-09, and 5.93e-10. Even at 60 kilometers of fiber, the bit error rate is within the (e-08) wireless communication limits. As a result, the system works well for long-distance communication.

The OSNR ratio can also be used to investigate the WDM-RoF system. The system performance suffers due to optical amplifiers such as EDFA, SOA, and Raman amplifiers. The OSNR is defined as the ratio of received optical signal power to noise power over a given frequency band. Table 5 shows the OSNR to determine the degradation of the output optical signal. The OSNR at 30 km optical length for channels 1 to 8 was 54.21, 54.35, 45.01, 32.67, 31.51, 30.68, 29.47, and 28.28dB, respectively, according to table 4. However, at a distance of 70 km, the OSNR ratio dropped to 51.39, 49.71, 40.54, 30.70, 25.89, 25.17, 24.75, and 24.07dB. The OSNR ratio of a WDM system must be greater than 20 dB for it to have a minimum BER of e-08. Table 4 shows that the above system can operate well up to at least 60 km. The design system uses fewer optical amplifiers to achieve a low optical signal-to-noise ratio.

The optical comprehensively picture a comprehensive picture of a system's performance. However, the electrical signal-to-noise ratio will provide system performance for long-distance communication. When a luminance signal falls on a photodiode, amplified spontaneous emission (ASE) noise causes further signal degradation. As a result, Table 6 provides a clear picture of the performance of the designed system's output signal-to-noise ratio.

Table 6 shows that the output SNR in dB at 30 km for channels 1 to 8 was 58.19, 58.33, 48.99, 36.65, 35.49, 34.66, 33.45, and 32.26, respectively. At 60 km of fiber optic, it drops to 56.15, 55.15, 46.06, 34.76, 31.76, 30.66, 29.84, and 29.48 dB. Still, the design system performs better because the required SNR is greater than 20 dB to have a minimum BER value. Noise from ASE (amplified spontaneous emission) is also reduced at the output.

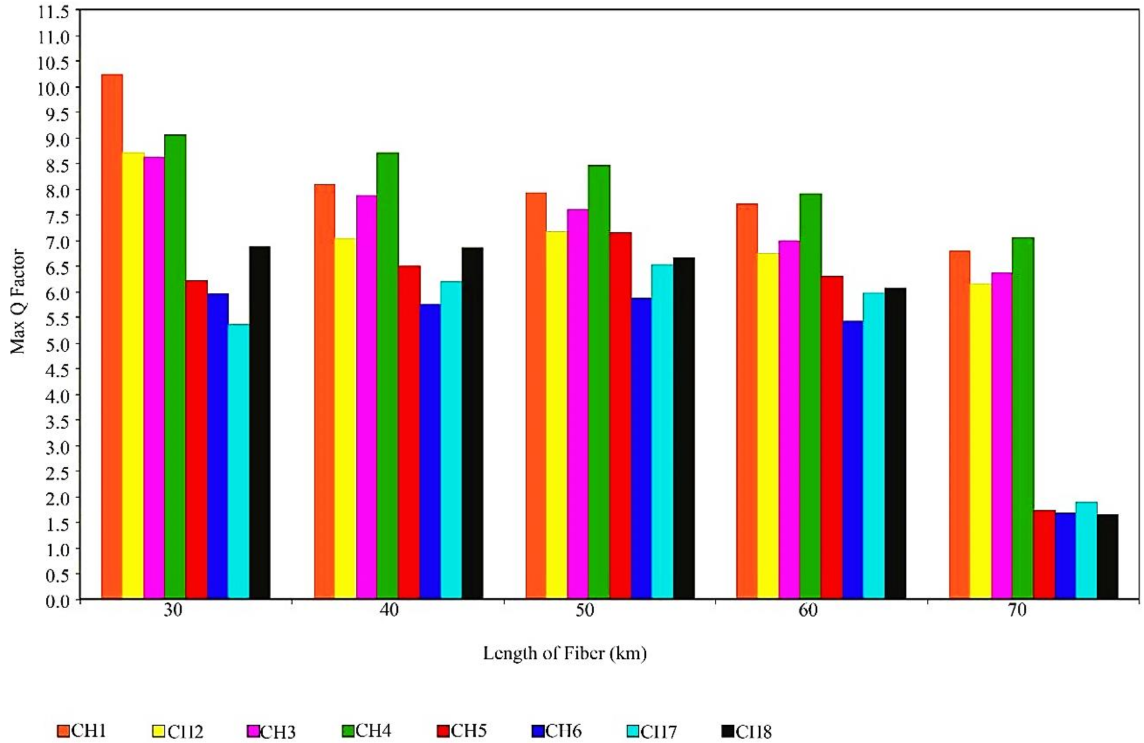


Fig. 3 Quality factor

Figure 3 shows that the quality factor of the designed system was significantly higher than the desired value Q factor for a minimum bit error rate at the output. Channels 1–4 in the C band have a quality factor decrease of around 2 dB for fiber lengths ranging from 30 km to 60 km. However, the L band channels 5 to 8 slightly decrease the quality factor by about 0.2 dB. As a result, the designed system performs better within a range of 60 km of fiber.

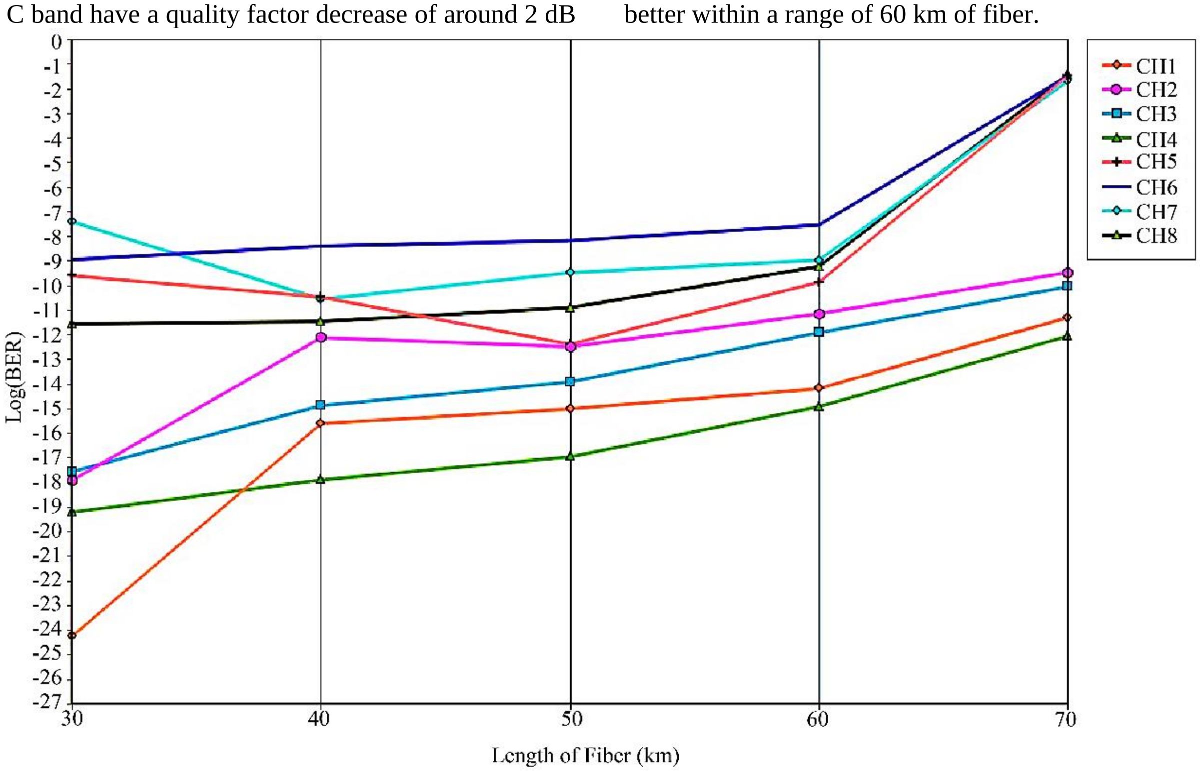


Fig. 4 BER curve

Figure 4 illustrates the BER curve of an eight-channel WDM Radio over a Fiber system. A bit error rate curve is critical for analyzing system performance in an optical fiber communication system. At 30 km of optical fiber, the BER value for the designed system was deficient. As a direct consequence, BER is proportional to fiber length. BER rises to 6.62e-15, 7.24e-12, 1.23e-12, 1.22e-15, 1.38e-10, 2.94e-08, 1.08e-09, and 5.93e-10 at 60 km. Figure 4 demonstrates that the proposed method performs better, achieving distances of up to 65 km.

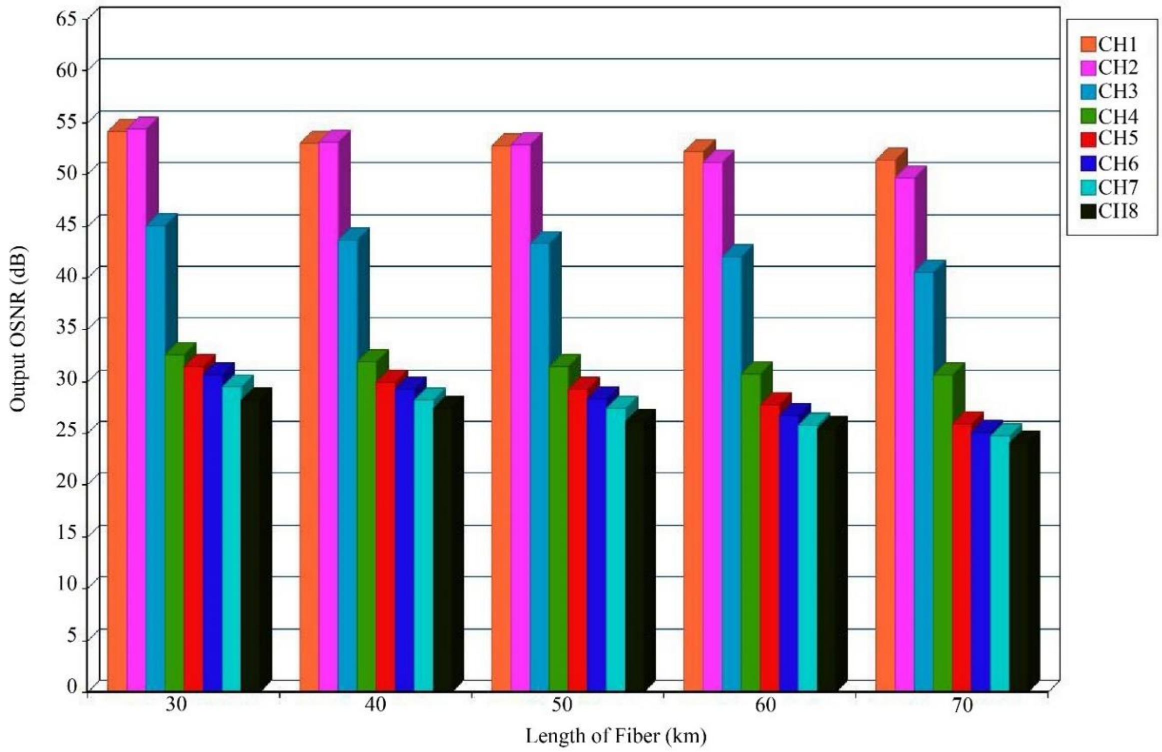


Fig. 5 OSNR ratio

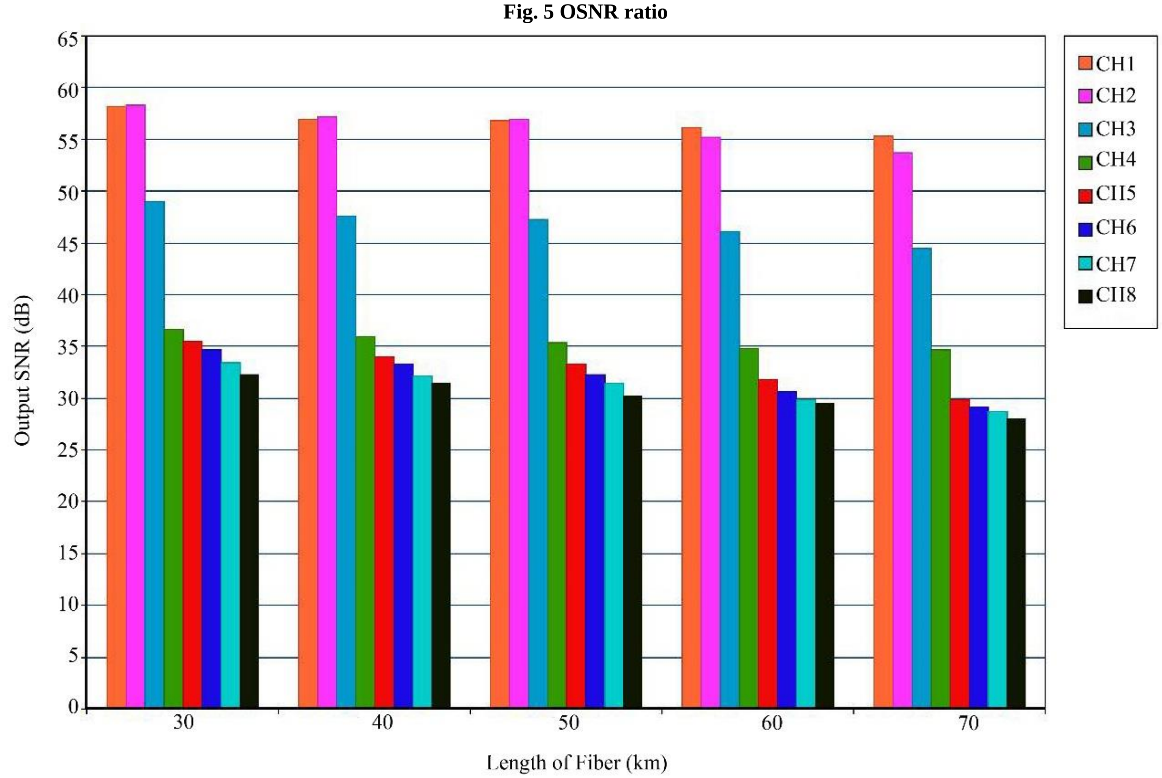


Fig. 6 SN

Figure 5 illustrates the OSNR bar chart for the designed WDM Radio over the Fiber system. The OSNR is an essential measure for determining the optical system's health. The OSNR Ratio is higher at 30 km and slightly lower at 60 km. At a distance of 60 km, the OSNR ratios for the eight channels were 52.17, 51.17, 42.08, 30.78, 27.78, 26.69, 25.86, and 25.50 (dB), respectively. It drops by 2.5 dB for the four C band channels and about 3 dB for the L band channels from 30 to 60 km of fiber length.

Figure 6 depicts an SNR bar chart for the system under consideration. The desired SNR value is around 20 dB to have an acceptable bit error rate at the receiver. The graph shows that the system works well above 20 dB to have the best electrical the SNR ratio is very high at shorter distances, and the SNR ratio is very high, gradually decreasing beyond 40 km. Figure 6 illustrates that the SNR ratio significantly reduces by about three (dB) over a range of 70 km for the four C band and L band channels.

Figure 7 characterizes the optical spectrum of the eight channels in the WDM Radio over the Fiber system. The two peaks at 1.55 m and 1.77 m represent the four channels in the C and L bands, respectively. Channels 1-4 in the C band have wavelengths ranging from 1550 to 1553 nm. However, the wavelengths of L band channels 5 through 8 are 1570 nm, 1570.5 nm, 1571 nm, and 1571.5 nm, respectively. Figure 7 shows that the maximum optical power is 0.197 dBm and the minimum power is -104.77 dBm for a laser power of -5 dBm. In the optical spectrum graph, the green hue implies noise present in the desired signal, while the red hue signifies signal power.

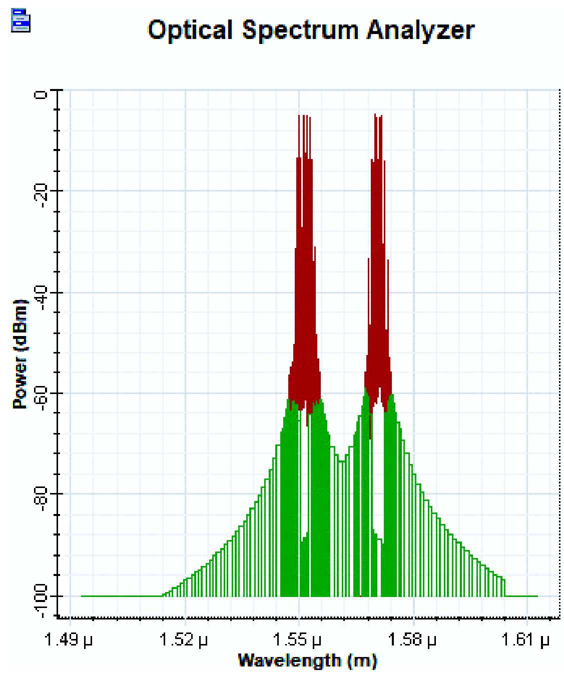
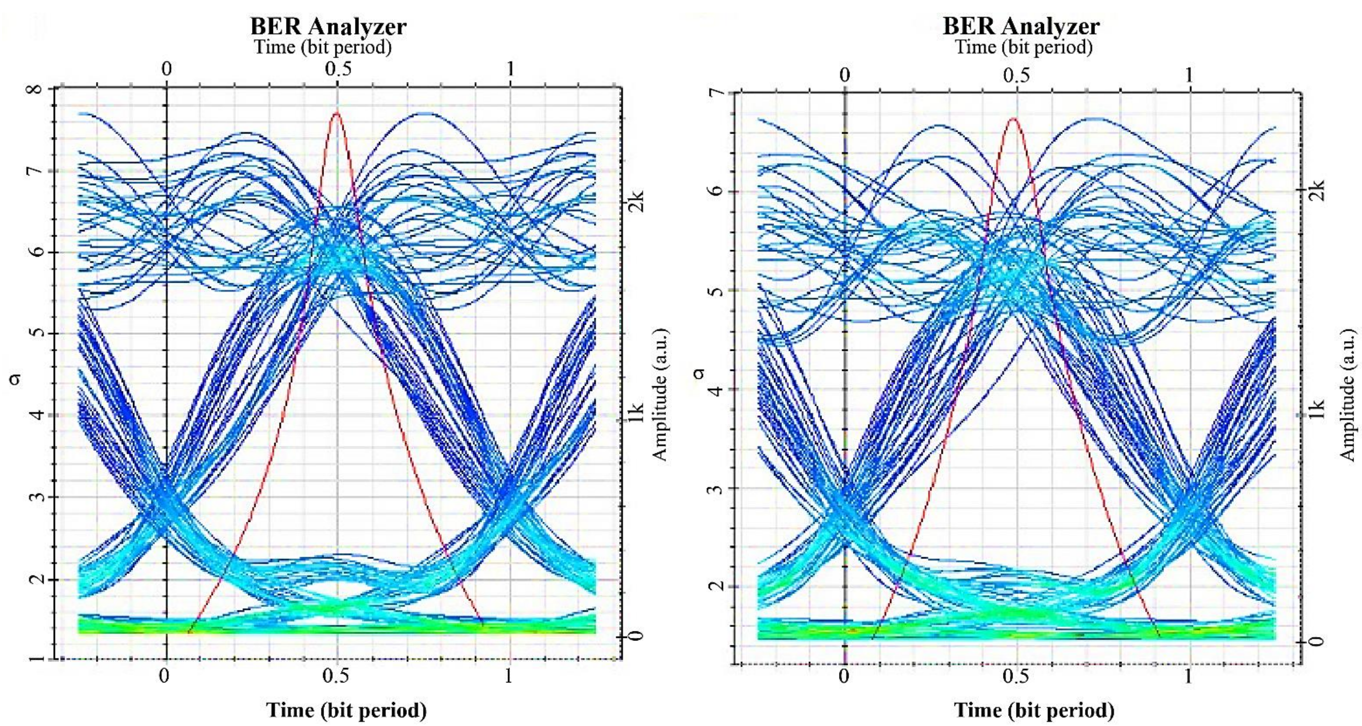
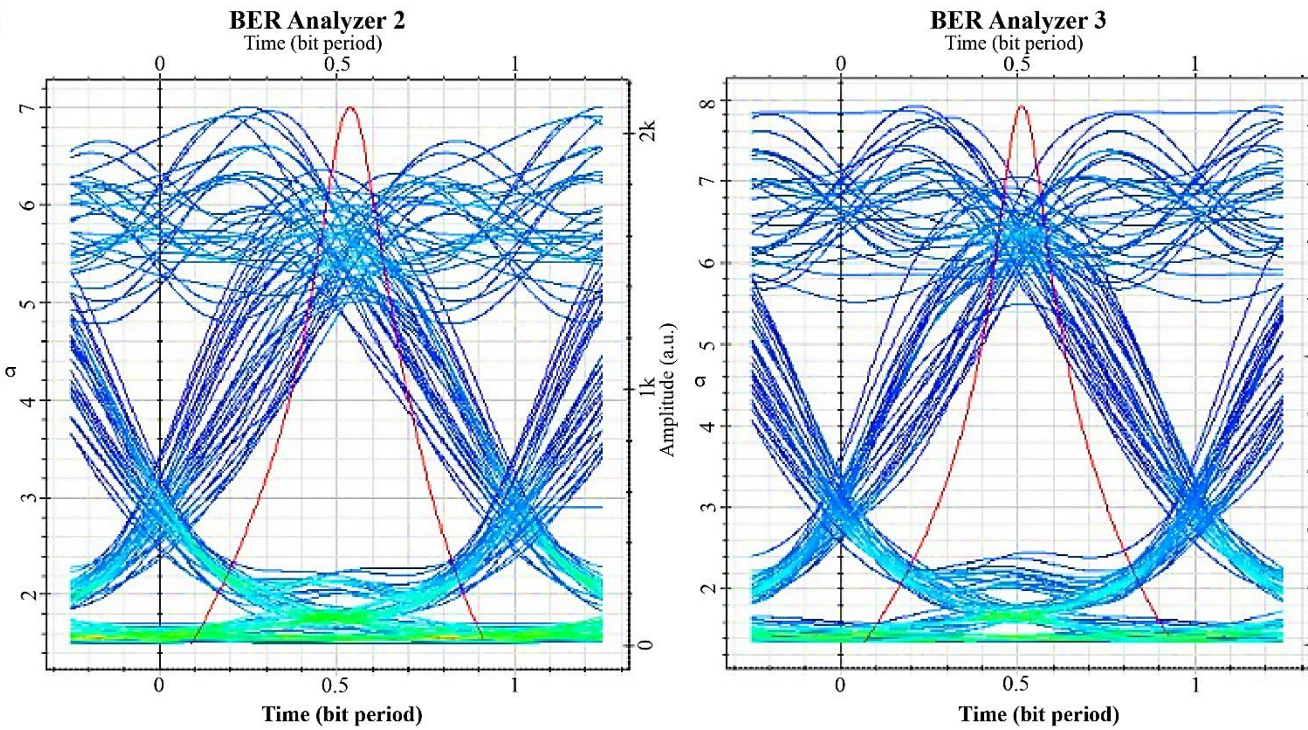


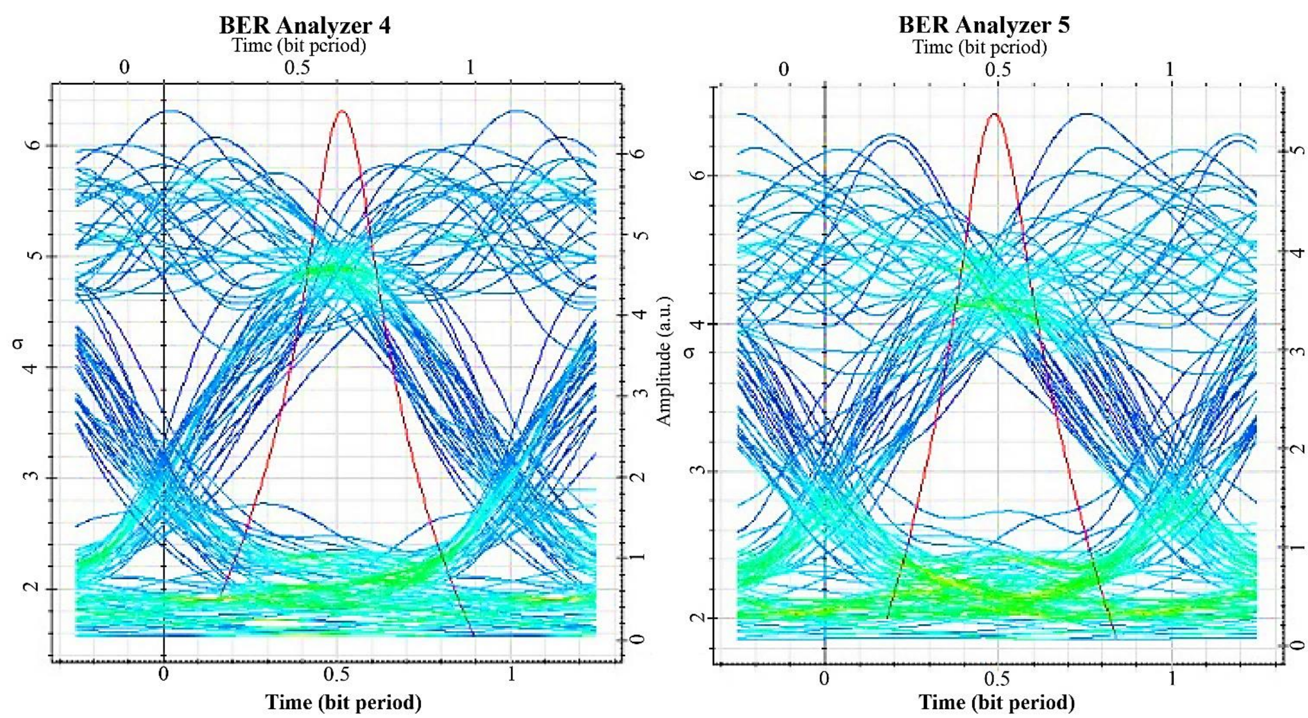
Fig. 7 Optical spectrum



8 (A)


BER Analyzer 2
Time (bit period)
Time (bit period)
Amplitude (a.u.)
BER Analyzer 3
Time (bit period)
Time (bit period)
Amplitude (a.u.)

8 (B)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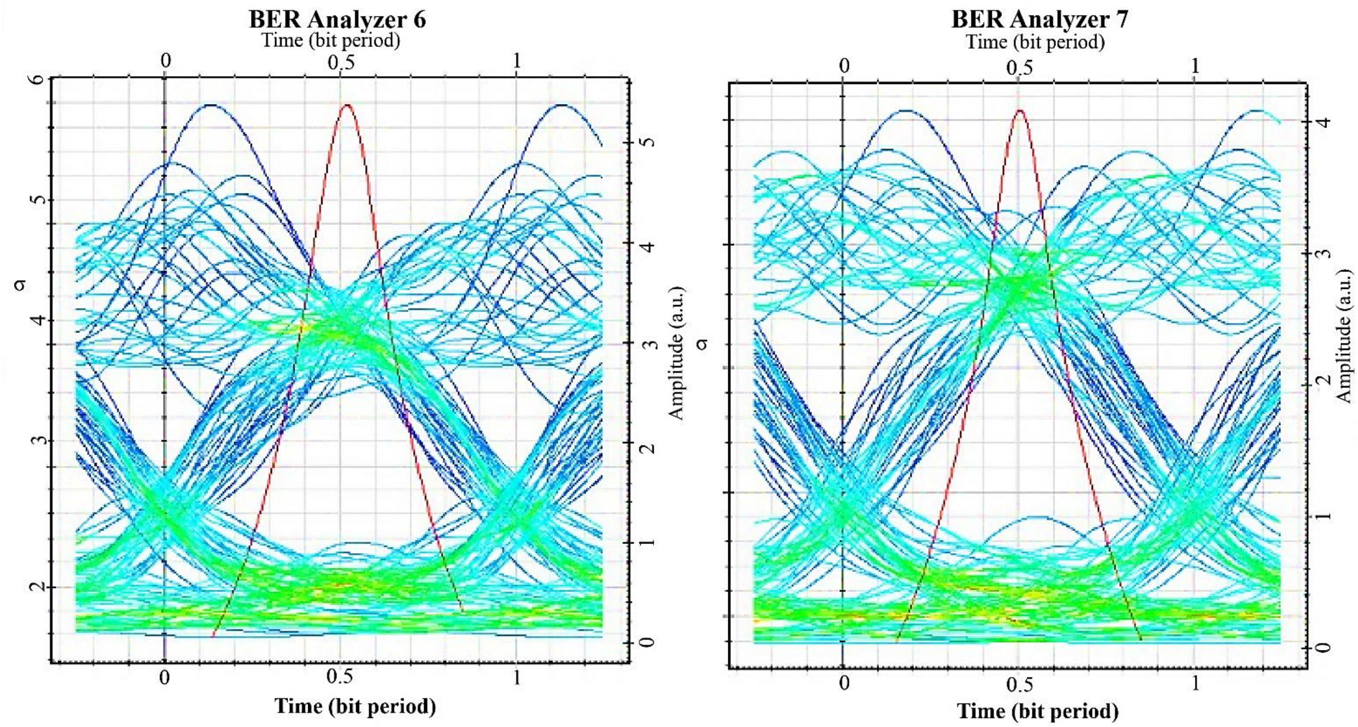
Time (bit period)
Amplitude (a.u.)
BER Analyzer 5
Time (bit period)
Time (bit period)
Amplitude (a.u.)

8 (C)



8 (D)

Fig. 8 Eye pattern proposed at 60 km for (A) Channels 1-2 (C band) (B) Channels 3-4 (C band) (C) Channels 5-6 (L band) (D) Channels 7-8 (L band)

Figures 8A, 8B, 8C, and 8D depict the eye pattern of the proposed method at 60 km for Channels 1-2, 3-4, 4-5, and 7-8, respectively. These patterns can be obtained by sampling the incoming signal at a predetermined time interval called the sampling period. These samples are applied to the oscilloscope's vertical plate, and the transmitted data rate is applied to the horizontal plate. A Lissajous pattern known as an eye diagram or eye pattern is then observed on CRO. The BER analyzer achieves the eye pattern in this designed simulation. The eye diagram determines the amount of error in received digital information. The amount of error is estimated using eye height. Figure 8 shows the eye heights for the C band channels 1–4: 994.49 au, 838.74 au, 816.36 au, and 804.26 au.

In contrast, the L band channels 5–8 were 2.06 au, 1.34 au, 1.32 au, and 1.19 au, respectively. The C band channels had a higher eye height because their wavelengths were closer to the single mode fiber's reference wavelength (1550 nm). The eye heights for the L band channels were small because the wavelength was far from the reference wavelength of the fiber. The eye patterns for the designed system are perfect and wide. As a result, this system can be used for up to 60 km without a problem.

4. Conclusion

The article examines an eight-channel wavelength division multiplexed RoF system. The proposed approach can be applied to 5G and other communication applications. Optisystem 19 was used to simulate the system. It is the most recent and widely employed optical system simulation software. The majority of WDM RoF systems only use the C band. However, due to the large number of applications running in this band, the C band is extremely congested. Another low attenuation L-band must be included in the WDM RoF system.

Table 7. Comparison of the current method to previous work-

Ref no	No of channels	Data rate (Gbps)	Band	BER	Amplifier	Laser pumping (dBm)	FIBER LINK (km)
3	8	112	C	e-5 to e-7	SOA	0 to -4	10
7	8	20	C	0	EDFA	10	90
8	8	20	C	e-7 to e-10	EDFA	0	100
10	16	160	C	e-267	EDFA	-	80
12	8	20	C	e-14	Optical amplifier	-10	100
17	8	96	C	e-58	Optical amplifier	0	120
Proposed method	**8**	**80**	**C and L**	**e-8**	**EDFA**	**-5**	**70**

The proposed approach combines the C and L bands to serve the high data rate and large bandwidth required for 5G and beyond communication. By referring to tables 2, 3, 4, 5, 6, 7 and figures 3, 4, 5, 6, 7, and 8, the designed method provides a high-quality factor and a low bit error rate.

According to table 7, other approaches only used the traditional C band, which is now very crowded, so researchers focused on the less crowded and low attenuation L band. In comparison, the current approach attempted to combine the low attenuation C and L bands for high data rate transmission of 80 Gbps in a WDM-RoF system. In ref. [17], a generalized optical amplifier with only a C band was used. On the other hand, the proposed method uses a low-cost EDFA amplifier and a very low laser power of -5 dB. In addition, for increased bandwidth requirements, both low attenuation C and L bands are included. The proposed method can accommodate the C and L bands for high data rates of up to 80 Gbps transmission. As a result, the method presented in this article is far superior to the previous approach. It is a new approach for using both the C and L bands in a WDM Radio over a Fiber system for high-speed, next-generation communication.

Different figures of merit, such as the eye diagram, quality factor, bit error rate, OSNR, and SNR ratio, are used to analyze and evaluate the proposed approach. Using single-mode fiber, this system successfully operated over 60 km. The proposed method provides Q factor and BER of 7.70, 6.74, 6.99, 7.91, 6.31, 5.42, 5.98, 6.08 and 6.62e-15, 7.24e-12, 1.23e-12, 1.22e-15, 1.38e-10, 2.94e-08, 1.08e-09, 5.93e-10 for the 8 channels over 60 km of optical fiber. Hence it is concluded that the method presented in this article is far better than the previous approach.

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