



Available Online at www.hithaldia.in/locate/ECCN
All Rights Reserved

ORIGINAL CONTRIBUTION

Performance analysis of Modified 16-Channel WDM-RoF network for Efficient Long-Haul 5G Communication

Suman Singh¹, Priyanka Dalal¹, Pravesh Kumari¹ and Sanjeev Kumar Dhull¹

Guru Jambheshwar University of Science and Technology, Dept. of E.E.E., Hisar, India

Email Id: priyanka.dalal17@gmail.com

ABSTRACT

This paper presents the design and performance evaluation of a 16-channel Wavelength Division Multiplexed Radio-over-Fibre (WDM-RoF) system for long-haul 5G communication networks. The proposed architecture integrates Fiber Bragg Gratings (FBGs) and an Optical Phase Conjugator (OPC) to enhance signal quality. The FBGs provide precise wavelength filtering and dispersion management, while the OPC effectively compensates nonlinear distortions, improving spectral efficiency and transmission reach. The system is designed to operate at a carrier frequency of 50 GHz with a data rate of 10 Gbps per channel and a channel spacing of 0.5 nm, achieving reliable transmission over 340 km of standard single-mode fiber. Simulation results demonstrate that the proposed 16-channel WDM-RoF model exhibits superior performance compared to conventional configurations, offering enhanced signal integrity, reduced dispersion effects, and improved scalability for high-capacity long-haul communication.

KEY WORDS: WDM-RoF, Wavelength Division Multiplexing, Fiber Bragg Grating (FBG), Optical Phase Conjugation (OPC), Long-Haul Communication, 5g Networks.

1. INTRODUCTION

The ever-growing number of wireless communication users, combined with the demand for higher data rates, has led to the migration from conventional frequency bands to higher frequency ranges such as the millimetre-wave (mm-wave) spectrum. These high-frequency bands are critical for addressing the requirements of next-generation communication systems, particularly 5G and beyond, which demand ultra-high capacity, low latency, and reliable connectivity [1-4].

Optical fiber has established itself as the most effective transmission medium for Radio-over-Fiber (RoF) systems due to its unique properties, including low attenuation, lightweight nature, high bandwidth, cost efficiency, and immunity to electromagnetic interference [5-6]. These features make optical fiber an efficient medium for transporting radio frequency (RF) signals over long distances while maintaining signal fidelity [7-9]. Compared with traditional

wireless transmission methods, RoF technology leverages the vast bandwidth of optical fibre to support a significantly larger number of users and higher transmission rates [10-12].

To enable long-haul RoF transmission, optical amplification is often required. Erbium-Doped Fiber Amplifiers (EDFAs) play a key role in boosting signal strength, compensating for transmission losses across fiber spans [13]. In Wavelength Division Multiplexed Radio-over-Fibre (WDM-RoF) architectures, additional components such as Mach-Zehnder Modulators (MZMs) are employed for efficient signal modulation, while Optical Phase Conjugators (OPCs) mitigate the effects of nonlinearities [14-15]. OPC effectively compensates for impairments caused by self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM), thereby improving system performance. Dispersion management is equally important, with Dispersion Compensating Fiber (DCF) commonly utilized to

counteract chromatic dispersion in WDM transmission [16-18].

Despite these advancements, optical fiber communication still suffers from impairments such as attenuation, dispersion, and nonlinear effects, which degrade overall system performance [5][6]. To address these limitations, Fiber Bragg Gratings (FBGs) have been widely deployed in multi-channel WDM systems to suppress unwanted reflections, filter specific wavelengths, and reduce dispersion-induced distortions. By providing accurate wavelength selectivity and dispersion control, FBGs significantly enhance system efficiency and stability [19-20]. Consequently, WDM-RoF has emerged as a promising solution for robust, high-capacity, and scalable communication networks [21]. Building upon prior research on 4-channel and 8-channel WDM-RoF systems, this work advances the field by developing and analyzing a 16-channel WDM-RoF architecture [22]. The proposed system integrates OPC and FBG components to improve signal integrity, suppress nonlinear impairments, and extend transmission distance, thereby addressing the increasing demands of long-haul 5G communication networks [23-24]. The operation of FBGs is based on the Bragg reflection principle, where the central reflected wavelength is determined by the following relation:

$$\lambda_{Bragg} = 2\eta_{ef} \Lambda(1)$$

Where, η_{ef} is the core effective index, and Λ is the grating period. The scalability and performance of the system are validated through simulation, demonstrating its potential as a cost-effective and reliable approach for next-generation communication infrastructures.

2. SYSTEM DESIGN

The proposed 16-channel WDM-RoF system is modelled and analysed using OptiSystem simulation software. The setup employs multiple continuous-wave (CW) laser sources, each operating around the standard reference wavelength of 1550 nm, with a uniform channel spacing of 0.5 nm, as illustrated in Fig. 1. This configuration ensures efficient wavelength allocation and supports high-capacity transmission. The overall architecture of the system is divided into two primary subsystems: the transmitter and the receiver, as depicted in Fig. 2, Fig. 3 and Fig. 4, respectively. At the transmitter side, each laser source is externally modulated using a dual-drive Mach-Zehnder Modulator (MZM). This modulation scheme enables efficient conversion of electrical data signals into the optical domain, ensuring broad bandwidth and stable transmission.

Table 1: Wavelength utilization in the proposed system corresponding to each channel.

Channel No.	Wavelength (nm)	Channel No.	Wavelength (nm)
Ch 1	1550	Ch 9	1554
Ch 2	1550.5	Ch 10	1554.5
Ch 3	1551	Ch 11	1555
Ch 4	1551.5	Ch 12	1555.5
Ch 5	1552	Ch 13	1556
Ch 6	1552.5	Ch 14	1556.5
Ch 7	1553	Ch 15	1557

The multiplexed optical signals are then combined to form a 16-channel WDM stream, which is transmitted over a 340 km single-mode optical fiber link.

To mitigate transmission impairments such as chromatic dispersion and nonlinear distortions, an OPC is strategically placed along the transmission path. The OPC generates a

conjugated replica of the distorted signal, effectively cancelling phase-related distortions and improving system linearity. In addition, FBGs are employed as wavelength-selective filters to manage dispersion, suppress crosstalk, and enhance wavelength stability, thereby improving signal integrity across all channels.

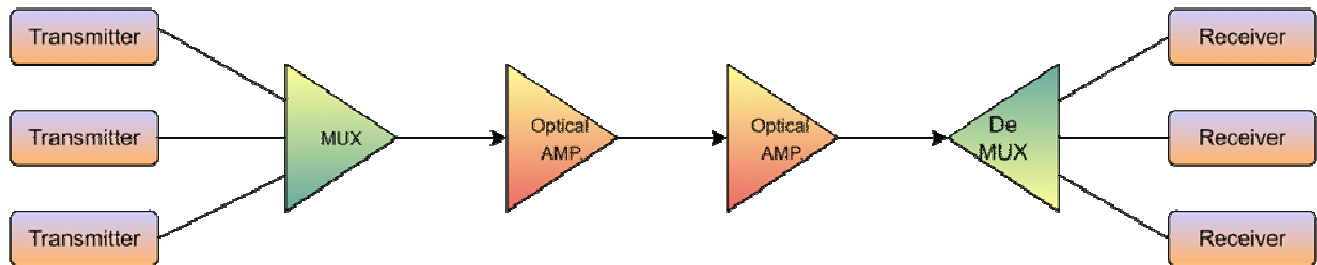


Figure1: Basic Block diagram of the WDM- RoF network

At the receiver side, an APD is utilised for optical-to-electrical conversion. The APD is selected for its high sensitivity and low-noise characteristics, which are particularly advantageous for detecting weak signals after long-distance transmission. A low-pass electrical filter is further employed to suppress high-frequency noise components, ensuring accurate signal recovery.

Finally, WDM analysers and optical spectrum analysers are integrated into the design to

evaluate key system performance metrics. These include OSNR and SNR and other transmission quality indicators that reflect the efficiency of the proposed 16-channel WDM-RoF model. The strategic use of OPC and FBG elements, combined with effective detection techniques, ensures improved signal quality, enhanced data rates, and robust performance over long-haul optical communication links.

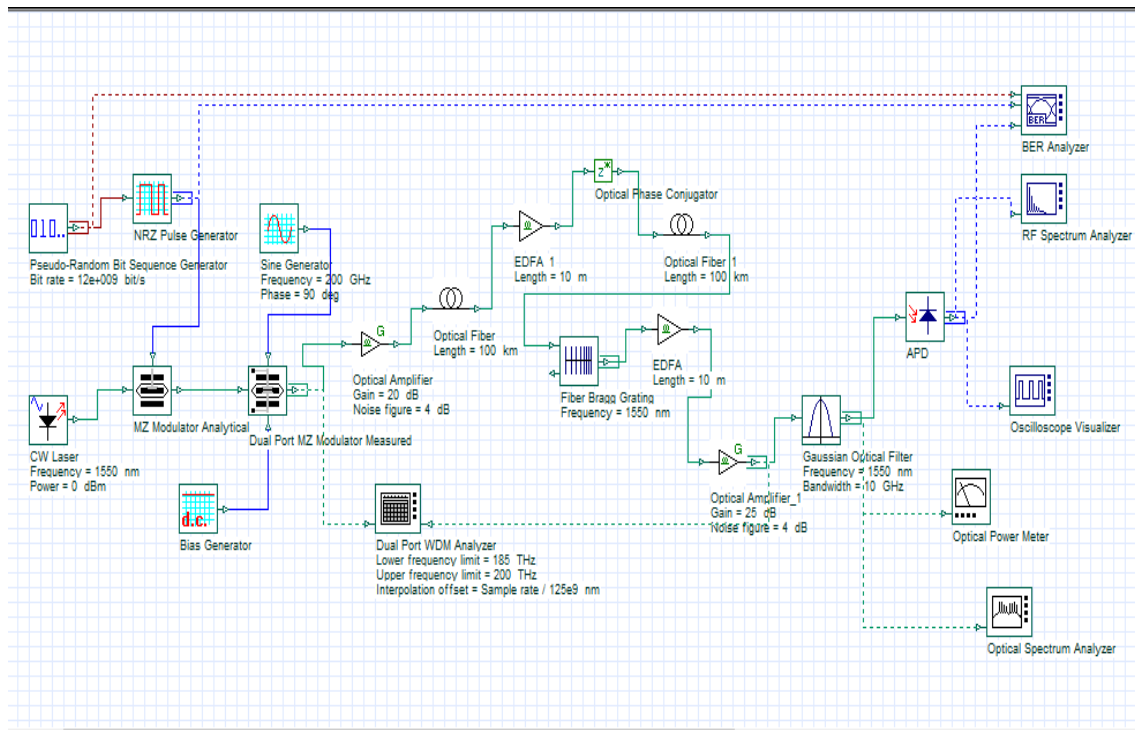


Figure 2: Schematic layout of the proposed single-channel WDM-RoF system.

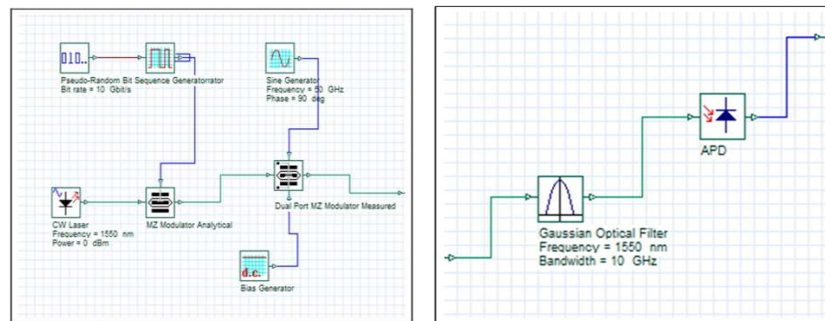


Figure 3: Sender Figure 4: Recipient

The figure illustrates the overall configuration of the designed RoF system. On the transmitter side, a Pseudo-Random Bit Sequence (PRBS) generator produces input data, which is encoded using a Non-Return-to-Zero (NRZ) encoder and modulated through a Mach-Zehnder Modulator (MZM). A continuous-wave laser operating at 1550 nm serves as the optical carrier, while a

dual-drive LiNbO₃ MZM is employed for external modulation, enabling efficient optical signal generation. The modulated signals are transmitted over a single-mode fiber link.

Figure 2 illustrates the simulated single-channel WDM-RoF system incorporating FBG and OPC [25].

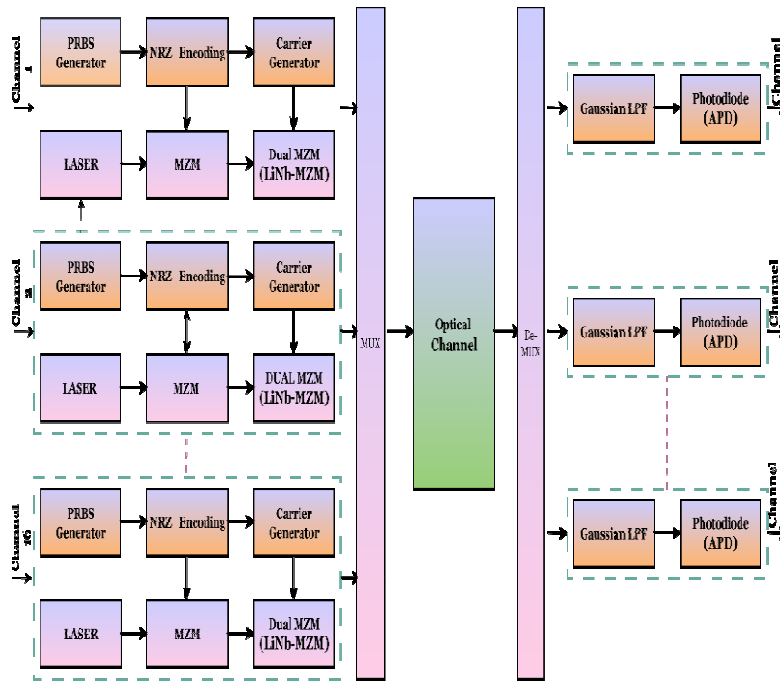


Figure 5: Schematic layout of the proposed 16-channel WDM-RoF system.

To mitigate impairments accumulated during long-haul transmission, an OPC is placed mid-span, in conjunction with an FBG for dispersion and nonlinearity management. At the receiver end, the optical signals are passed through a Gaussian low-pass filter before being detected by an APD, ensuring improved sensitivity and reduced noise. The overall configuration enhances transmission performance, providing improved signal quality over extended distances.

Figure 5 shows the proposed 16-channel WDM-RoF network, with transmitters and receivers represented as blocks, while their internal architectures are detailed in Figures 3 and 4, respectively.

Figure 2 illustrates the simulated single-channel WDM-RoF system incorporating FBG and OPC [25]. The transmitter configuration of the proposed 16-channel WDM-RoF system integrates several functional components, including a PRBS generator, NRZ pulse encoder,

continuous-wave laser source, sinusoidal oscillator, DC bias generator, and a dual MZM, as outlined in Fig. 3. The WDM transmitter enhances the transmission capacity by producing multiple optical carriers at distinct wavelengths and subsequently combining them into a single optical fiber using a multiplexer. In this design, 16 unique carrier frequencies are generated.

To address nonlinear distortions in the fiber link, OPC is employed in conjunction with distributed optical amplifiers and dual fiber spans. OPC, also referred to as wavefront reversal, produces a conjugated optical wave by inverting the phase of the original signal. Representing the input optical field as:

$$E_{in}(t) = A(t)e^{j\phi t} \tag{2}$$

the phase-conjugated signal is mathematically equivalent to taking the complex conjugate of the input, yielding:

$$E_{out}(t) = \eta A(t)e^{-j\phi t}e^{j\phi_{shift}} \tag{3}$$

where η represents the device efficiency. The combination of OPC with reversed propagation effectively compensates for nonlinear phase distortions and waveform impairments encountered in optical transmission.

FBG operates on the principle of Bragg reflection, which occurs due to a periodic refractive index modulation within the optical fiber. This periodic structure is inscribed along a specific length of the fiber, unlike the uniform refractive index of a standard fiber core that typically allows light to propagate without reflection.

However, when a periodic refractive index modulation is introduced, it forms a “grating” structure within the fiber. The refractive index modulation is typically achieved by using an ultraviolet (UV) laser to expose the fiber core to intense UV light through a phase mask or interferometric technique. The UV light causes a photosensitive change in the fibers refractive index, resulting in a periodic fluctuation in the refractive index profile. When light propagates through the fiber and encounters the FBG, a portion of the incident beam is returned due to the periodic refractive index modulation. This reflection occurs at a certain wavelength resolved by the period of the grating. This wavelength is called the Bragg wavelength (λ_{Bragg}) and is given by the Bragg condition [1][25].

$$\lambda_{Bragg} = 2 * \Lambda * n_{eff} \quad (4)$$

where,

Λ = the period of the grating

n_{eff} = the effective refractive index

The Bragg condition guarantees that reflected light waves undergo constructive interference, thereby producing a strong reflection precisely at the Bragg wavelength. Conversely, wavelengths outside this range propagate through the grating with negligible reflection. By adjusting the grating period and fabrication parameters, an FBG can be tailored to operate either as a narrowband reflector or as a broadband filter. Moreover, tilted grating structures can be employed to control the reflection angle, offering additional flexibility in design.

On the receiver side, the system integrates a wavelength demultiplexer, a Gaussian optical filter, and an APD shown in Fig. 4. The demultiplexer separates the multiplexed optical carriers into their individual channels, after which the Gaussian filter suppresses unwanted noise and out-of-band components. The filtered signal is then converted into an electrical domain by the APD. To restore the original data quality, a signal regenerator is incorporated, while a (BER) tester evaluates system performance in terms of OSNR and SNR under varying distances. Table 2 outlines the simulation parameters used in this study along with their assigned values.

Table 2. Simulation factors.

Parameter	Value
Modulation Scheme	LiNb-MZM

Bit rate	10 Gbps
Radio signal frequency	50 GHz
Reference wavelength	1550 nm
Wavelength spacing	0.5 nm
OSNR & SNR Measurement	WDM Analyzer

3. RESULTS AND DISCUSSIONS

The system is designed using OptiSystem, and its performance is evaluated in terms of OSNR and SNR with respect to transmission distance, bit rate, and carrier frequency.

The simulated performance of the proposed 16-channel WDM-RoF system is analyzed in terms of key quality metrics, namely OSNR and SNR. Particular emphasis is placed on evaluating the impact of increasing transmission distance on system efficiency. The assessment is carried out for distances ranging from 50 km to 340 km, thereby enabling an in-depth understanding of the system's transmission capability over long-haul fiber links.

Each of the 16 channels operates within the wavelength range of 1550 nm to 1557.5 nm, with a uniform channel spacing of 0.5 nm. The system is simulated at a data rate of 10 Gbps per channel and a 50 GHz RF carrier frequency,

providing a robust basis for performance evaluation. The simulation results are summarised in Tables 3 and 4, corresponding to OSNR and SNR variations across different channels and transmission distances.

Table 3 presents the OSNR values (in dB) for the 16-channel system. The results demonstrate a gradual reduction in OSNR with increasing fiber length. For example, Ch 1 records an OSNR of 53.31 dB at 120 km, which decreases to 31.35 dB at 340 km, whereas Ch 15 shows 35.13 dB at 120 km, reducing to 17.08 dB at 340 km. The analysis confirms that the OSNR values across all channels remain above the minimum acceptable threshold of 16 dB within the range of 120 km to 340 km, as illustrated in Fig. 6. This indicates that the proposed system ensures reliable transmission performance over long-haul distances. However, the expected degradation in OSNR with distance is primarily attributed to fiber attenuation and chromatic dispersion.

Table 3. Variation of OSNR (dB) for Ch 1 to 16 with transmission distance.

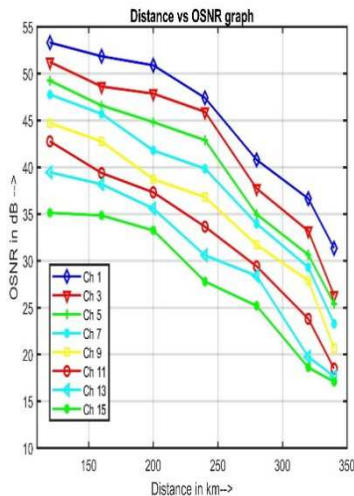
Distance (km)	Channel (Wavelength (nm))							
	Ch 1	Ch 3	Ch 5	Ch 7	Ch 9	Ch 11	Ch 13	Ch 15
120	53.31	51.24	49.24	47.76	44.17	42.76	39.45	35.13

160	51.85	48.62	46.59	45.70	42.75	39.38	38.19	34.85
200	50.89	47.86	44.82	41.79	38.72	37.32	35.59	33.25
240	47.41	45.92	42.89	39.85	36.81	33.65	30.59	27.79
280	40.79	37.73	34.98	33.97	31.71	29.41	28.40	25.19
320	36.65	33.20	30.65	29.31	27.89	23.81	19.75	18.61

Table 4 provides the SNR results for all 16 channels across the same transmission range. The trend is consistent with the OSNR observations, showing decreasing SNR with distance.

Table 4. Variation of SNR (dB) for Ch 1 to 16 with transmission distance.

Distance (km)	Channel (Wavelength (nm))							
	Ch 1	Ch 3	Ch 5	Ch 7	Ch 9	Ch 11	Ch 13	Ch 15
120	53.23	51.78	50.72	47.65	44.8	41.89	40.15	35.30
160	52.38	48.54	46.79	44.11	42.8	40.19	36.98	35.62
200	50.69	49.77	47.10	44.91	40.9	38.16	35.81	33.42
240	47.78	45.67	43.19	41.86	39.7	37.65	33.55	31.29
280	42.17	40.82	38.98	35.87	33.9	31.22	28.78	25.45
320	38.28	35.23	32.47	30.75	28.6	25.82	20.32	18.38



For instance, Ch 1 exhibits an SNR of 53.23 dB at 120 km, reducing to 30.41 dB at 340 km, while Channel 15 decreases from 35.30 dB at 120 km to 16.13 dB at 340 km. Despite this decline, the system maintains SNR values well

above 18 dB across all channels for distances up to 340 km, as depicted in Fig. 5. This highlights the system’s capability to support high-quality signal transmission, although dispersion and

attenuation effects remain significant limiting factors over extended distances.

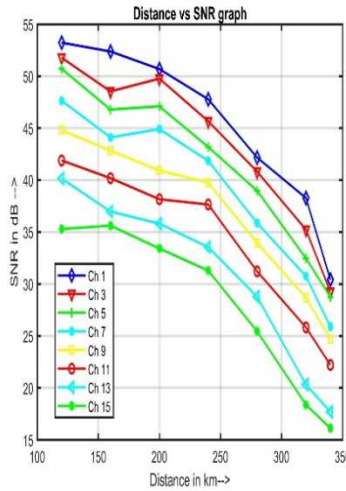


Figure 6: Distance vs OSNR

Figure 7: Distance vs SNR

Table 5. OSNR Comparison of the 16-Channel WDM-RoF Network: Proposed vs. Existing Work.

Distance	Existing Work[1]		Proposed 16-Channel WDM-RoF System						
	90 km	110 km	120 km	160 km	200 km	240 km	280 km	320 km	340 km
Ch 1	65.08	52.82	53.31	51.85	50.89	47.41	40.79	36.65	31.35
Ch 3	64.48	56.66	51.24	48.62	47.86	45.92	37.73	33.20	26.31
Ch 5	61.93	50.69	49.24	46.59	44.82	42.89	34.98	30.65	25.41
Ch 7	41.27	25.68	47.76	45.70	41.79	39.85	33.97	29.31	23.29
Ch 9	-	-	44.17	42.75	38.72	36.81	31.71	27.89	20.66
Ch 11	-	-	42.76	39.38	37.32	33.65	29.41	23.81	18.49
Ch 13	-	-	39.45	38.19	35.59	30.59	28.40	19.75	17.65
Ch 15	-	-	35.13	34.85	33.25	27.19	25.19	18.61	17.08

A comparative evaluation of OSNR performance is provided in Table 5. The reference system achieves an OSNR, which is close to the acceptable threshold of 16 dB, thereby limiting its transmission capability. In contrast, the proposed 16-channel system consistently maintains OSNR above 16 dB across the extended distance of 340 km, demonstrating superior performance. Beyond this distance, however, a noticeable degradation in signal quality occurs, which could potentially impact link reliability.

Overall, the proposed system validates its effectiveness for long-haul communication up to 340 km, with all 16 channels achieving reliable OSNR and SNR performance.

For transmission beyond this limit, further system optimization, including advanced dispersion compensation techniques and amplification strategies, will be required to sustain high-quality communication

A comparative evaluation between the existing WDM-RoF systems and the proposed model is presented in Table 5 at a 10 Gbps data. Table 5 provides a detailed comparison of OSNR results obtained by Garg et al. (2022) and those achieved in the proposed model. Similarly. The results clearly indicate that the proposed network substantially outperforms the reference system, particularly at higher data rates and longer distances, where signal impairments typically degrade transmission quality.

Hence, the proposed design demonstrates a significant advancement in WDM-RoF technology, offering improved performance and

making it a strong candidate for deployment in next-generation communication infrastructures.

4. CONCLUSION

This paper presents a modified 16-channel WDM-RoF system designed for high-speed and long-distance data transmission, demonstrating reliable performance up to 340 km. The system incorporates advanced technologies such as OPC and FBG to mitigate dispersion and nonlinear impairments, thereby enhancing overall transmission efficiency.

Simulation results validate the system's robustness in terms of both OSNR and SNR. Across all 16 channels, OSNR values remain well above the acceptable threshold of 16 dB, even at the maximum evaluated distance of 340 km. For example, at 340 km, the lowest-performing channel still achieves OSNR and SNR values above the critical limits, ensuring reliable long-haul communication. Beyond 340 km, however, a gradual decline in performance is observed due to increasing attenuation and dispersion effects.

Comparative analysis further emphasises the superiority of the proposed system over existing WDM-RoF designs, as it maintains signal integrity and quality over extended distances where conventional systems fail to meet acceptable performance thresholds. Overall, the proposed 16-channel WDM-RoF system demonstrates significant potential for next-generation communication networks, offering enhanced capacity, efficiency, and reliability for diverse high-speed applications.

References:

- [1]. Garg, Deepak & Nain, Abhimanyu. (2022). An efficient 110×8 GHz WDM RoF system design for 5G and advance wireless networks. *Optical and Quantum Electronics*. 54. 10.1007/s11082-022-03726-4.

- [2]. Jain, Deepak & Iyer, Brijesh. (2021). Design and analysis of high-speed four-channel WDM Radio over Fiber system for Millimeter-wave applications. *International Journal of System Assurance Engineering and Management*. 10.1007/s13198-020-01051-1.
- [3]. S. Boss, S. Dahiya and P. Kumari, "Analysis Of Modified 8-Channel WDM-RoF System for long haul communication," 2024 Second International Conference on Microwave, Antenna and Communication (MAC), Dehradun, India, 2024, pp. 1-5, doi: 10.1109/MAC61551.2024.10837545.
- [4]. Zacharias, Joseph & Philip, Merin & S S, Supriya & Narayanan, Vijayakumar. (2017). 60 GHz OFDM Radio-over-Fiber system based on Fabry-Perot Laser Diode. 1-4. 10.1109/ICCPCT.2017.8074340.
- [5]. Vegas Olmos, J.J. & Tafur Monroy, Idelfonso. (2015). Reconfigurable Radio-Over-Fiber Networks [Invited]. *Journal of Optical Communications and Networking*. 7. B23. 10.1364/JOCN.7.000B23.
- [6]. Kumari P, Kumar V, Arya S. Design and Performance Analysis of 32-Channels WDM-RoF System. *Indian Journal of Pure & Applied Physics (IJPAP)*. 2025: 63; 612-616.
- [7]. Garg, Deepak & Nain, Abhimanyu. (2021). Next generation optical wireless communication: A comprehensive review. *Journal of Optical Communications*. 10.1515/joc-2020-0254.
- [8]. Garg, Deepak & Nain, Abhimanyu. (2023). Design and Investigation of an Improved FTTH Network for Superior Quality Triple-Play Services. 10.1007/978-981-99-0969-8_47.
- [9]. Konstantinou, Dimitrios et al. "5G RAN architecture based on analog radio-over-fiber fronthaul over UDWDM-PON and phased array fed reflector antennas." *Optics Communications* 454 (2020): 124464.
- [10]. Garg, Deepak & Nain, Abhimanyu. (2022). Analysis and mitigation of photodiode non-linearity under the influence of optical modulator in multitone RoF link. *Journal of Optics*. 51. 10.1007/s12596-021-00794-9.
- [11]. Yang, Tao & Gao, Mingyi & Qian, Jiaqin & Zhang, Junfeng & Chen, Wei. (2017). A flexible millimeter-wave radio-over-fiber system for various transmission bit rate. *Optics & Laser Technology*. 96. 132-140. 10.1016/j.optlastec.2017.04.012.
- [12]. Singh, Sarika & Arya, Sandeep & Singla, Shelly. (2019). A Study & Review of Various Optical Linearization Techniques for Next Generation RoF Networks. 125-133. 10.1109/ISPC48220.2019.8988358.
- [13]. Singh, Sarika & Arya, Sandeep & Singla, Shelly. (2020). Linearization of Photonic Link Based on Phase-Controlled Dual Drive Dual-Parallel Mach-Zehnder Modulator. *Wireless Personal Communications*. 114. 10.1007/s11277-020-07351-w.
- [14]. Garg, Deepak & Nain, Abhimanyu. (2022). Analysis and counter-measure of the FWM-induced crosstalk including contemporary optical fibers. *Optical and Quantum Electronics*. 54. 10.1007/s11082-022-04215-4.
- [15]. Kumari, Priyanka & Nain, Abhimanyu. (2018). Design and Simulation of RoF and FSO based Hybrid Network. 6. 1633-1636.
- [16]. Gaurav, Y., and R. K. Chauhan. "Performance Analysis of EDFA Gain Using FBG for WDM Transmission". *Journal of Telecommunication, Electronic and Computer Engineering*