WDM-RoF Architecture for Low-Cost and Large-Coverage 5G Applications

Safa Mohammed
Department of Electrical Engineering, Baghdad University of Engineering, Baghdad, Iraq
safa.abd2302m@coeng.uobaghdad.edu.iq (corresponding author)

Ismael Desher
Department of Electrical Engineering, Baghdad University of Engineering, Baghdad, Iraq
dr.esmael.s@coeng.uobaghdad.edu.iq

Received: 16 January 2025 | Revised: 3 February 2025 | Accepted: 9 February 2025

 DOI: https://doi.org/10.48084/etasr.10258

ABSTRACT

This paper presents an enhanced Wavelength Division Multiplexing (WDM) method based on the Radio over Fiber (RoF) architecture to achieve cost-effective, long-distance, and high-coverage communication for 5G systems. The proposed model addresses the critical challenges of increasing the number of channels and transmitting the Radio Frequency (RF) signal along 72 km distance while ensuring enhanced data rates and reduced latency across extensive coverage areas. Performance evaluations demonstrate that the 8-channel model (80 Gbps) has quality factors of 6.8, 7.5, 7.8, and 7.7, and the minimal Bit Error Rate (BER) is 2.9E-10, 2.2E-11, 2.2E-12, and 4.2E-12. The 16-channel model (160 Gbps) has quality factors of 5.6, 6.5, 6.8, and 6.9 with minimal BERs of 2.9E-8, 2.2E-10, 2.2E-10, and 4.2E-11, respectively. The 32-channel model (320 Gbps) has quality factors of 5.4, 6.1, 6.3, and 6.2 with minimal BERs of 2.9E-8, 2.2E-11, 2.2E-10, and 4.2E-10. The results highlight the potential of the proposed Wavelength Division Multiplexing Radio over Fiber (WDM-RoF) model to serve as a robust backbone for next-generation mobile networks, meeting the demands of 5G communication.

Keywords-mobile communication; radio over fiber; Wavelength Division Multiplexing (WDM); optical communication system

I. INTRODUCTION

With the global spread of 5G systems, the long distance high-speed communication is expected to be significantly improved [1, 2]. Optical fibers allow substantial information transfer and have become the prime technology tool for long-distance communications [3]. Radio signals with a range of a few GHz can carry light signals, satisfying power saving demands, lowering interference and noise, and reaching faraway destinations [4, 5]. Optical transmission systems face certain issues when supporting multiple users [6]. WDM has evolved to allocate separate wavelengths to each user through access points, thereby facilitating multiple users [7, 8]. However, this approach generates noise and interference problems and is sensitive to various factors [9]. Thus, the main purpose is to distribute users into specific access points with selected wavelengths according to the demands for optimal Signal-to-Noise Ratio (SNR) and minimum Quality of Service (QoS) [10].

The RoF technology is attractive for implementing wireless access networks. This technology can carry 5G millimeter waves over fiber optic links, enabling communication over short and long distances [11-13]. In the RoF process, optical RF linking is applied to allow uplink and downlink signal transmission in the modulated RF through optical fibers from the source starting from the endpoint and vice versa [14-16]. It must be pointed out that the various factors that would negatively affect the transmission system are concentrated in the transmission channel. The fiber used as a means of transmission has proven its worth due to its narrow core layer relative to the surrounding cladding layer, which is important in raising the electrical intensity and power supply at the sender side (Sx) to travel the allotted large distance to the receipting destination (Re). One of these influences is the nature of the channel and has a linear effect [17].

Several processors for the same model have been produced to solve the capacity and transmission distance issues. For example, the one channel model proposed in [18] had a booster amplifier and pre-amplifier added to increase the broadcast distance. The model in [19] had four channels boosted by 10 dB by an Erbium-Doped Fiber Amplifier (EDFA) to cover a 70 km transmission distance. The model in [20] had a new design consisting of two Single-Mode Fibers (SMFs) and an Optical Phase Conjugate (OPC) to enhance the bandwidth quality transmission over distances reaching 110 km. The model proposed in [21] extended the C band (1530-1565 nm) into the L band (1565-1625 nm) for low fiber optic attenuation and was chosen for RoF networks, as shown in Table I. In this work, the previous cost-effective model introduced in [13] is followed, which increases the data speed (increased number of channels) and transmission distance. Many significant changes were made to boost the transmission distance and data throughput by adding more channels:

- WDM implementation: The number of channels in the same optical cable has been expanded by using WDM. This method effectively multiplies the data capacity without the need for more fibers by allowing numerous data streams to be delivered simultaneously on various wavelengths.
- Enhanced Modulation Formats: Higher data rates are now possible within the same bandwidth thanks to the incorporation of sophisticated modulation methods, which have enhanced spectral efficiency. Increased data speed is made possible by this improvement without requiring more spectrum resources.
- Better Error Correction Mechanisms: The error correction protocols have been updated with more reliable methods to improve the system's resistance to signal deterioration over long distances and guarantee data integrity over long transmission spans.

When taken as a whole, these improvements have made the proposed concept a more potent and effective system that can support longer transmission lengths and faster data rates while remaining economically viable. The design followed in this work is limited to a specific cost, which means that the transmission optical channel consists of SMF with a dispersion coefficient D = 16.75 ps/nm/km and attenuation coefficient α=0.2 dB/km. The design is economically viable and has succeeded in satisfying a high number of channels except for achieving the desired high coverage distance.

TABLE I. LITERATURE REVIEW AND COMPARISON OF RADIO OVER FIBER-BASED WDM IN PREVIOUS MODELS

Reference No.	No. of channels	Data rate (Gbps)	RF signal (GHz)	Optical band	BER	Q-factor	Amplifier type	Laser pump (dBm)	Fiber link (km)
[18]	1	1 ×10	60	C	4.6e-23	9.8	EDFA	20	80
[19]	4	4 ×10	100	C	2.1e-9	5.8	EDFA	0	70
[20]	8	8 ×14	110	C	1.14e-5	4.2	EDFA	0	120
[21]	8	8 ×10	60	C-L	5.93e-10	6.08	EDFA +SOA	-5	60
[13]	4	4 ×10	60	C	-	-	NON	0	60

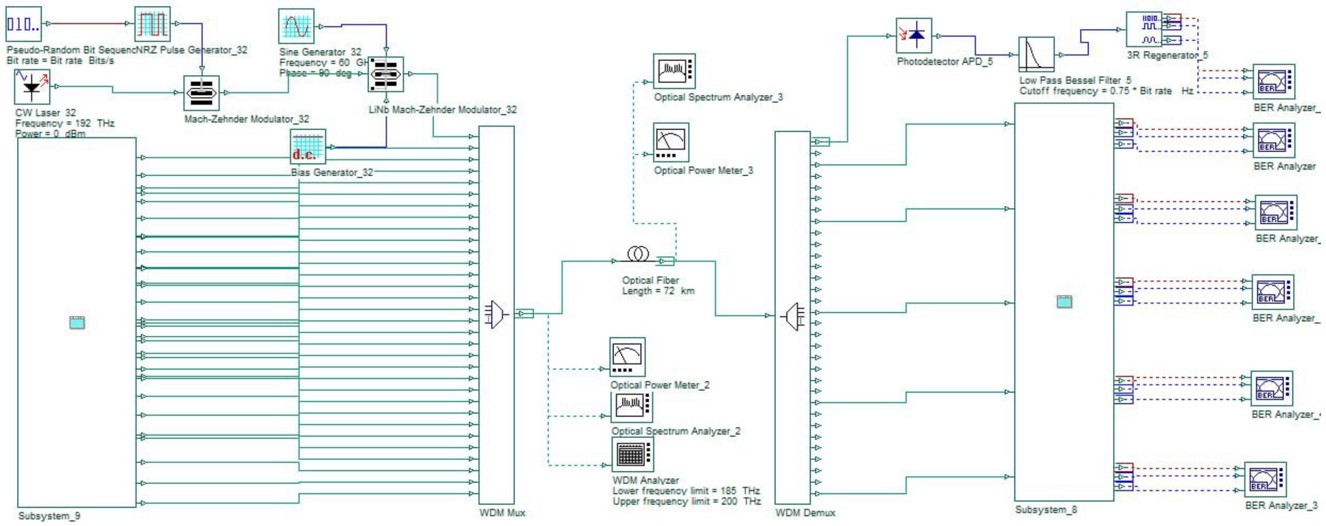


Fig. 1. Schematic of the cost-effective 32-channel WDM-RoF network model for 72 Km transmission distance.

II. MODEL SETUP

The model illustrated in Figure 1 represents a cost-effective design that consists of three main parts: the sender side, the receiver side, and the transmission channel. The 32 ×10 Gbps system was operated at Optiwave version 7.0. The model has 32 channels covering the whole C band (1530-1565 nm), starting from 192 -195.875 THz corresponding to 1531.5-1562.5 nm with a channel spacing of 125 GHz. The optical communication system is cost-effective starting with the sender side, as depicted in Figure 2, which contains an electrical terminal and a Pseudo-Random Binary Sequence (PRBS) generator with a Non-Return to Zero (NRZ) pulse generator, modulated with an optical wave source (CW) operating at 1.0 mW (0 dBm), with a line width of 10 MHz. The Mach-Zehnder Modulator (MZM) is the first modulator between the electrical form data of 10 Gbps on the optical carrier of 192 THz (first channel). The second dual MZM (LiNb) modulates the RF signal of 60 GHz with the optical carrier to make the input signals to the 32:1 multiplexer of WDM smoother. WDM is used to combine all 32 optical signals (from 192 to 195.875 THz) that carry the RF signals of 60 GHz as an optical beam and sends them into the optical transmission channel.

TABLE II. PARAMETERS USED IN THE WDM-ROF MODEL OF FIGURE 1

Parameters	Symbols	Values
Optical source frequency	ν	192 THz
Optical source Power	P	0 dBm
Sine waveform	RF signal	60 GHz
LiNb MZM	LiNb MZM	
Bias generator	I_{dc}	3 a.u.
SMF length	L	72 km
SMF dispersion coefficient	D	16.75 ps/nm/km
SMF attenuation	α	0.2 dB/km
SMF dispersion slope	S	0.075 ps/nm²/km
SMF effective area	A	80 μm²
Photodetector responsivity	R	1 A/W
LPBS cutoff frequency		0.75*Bit rate

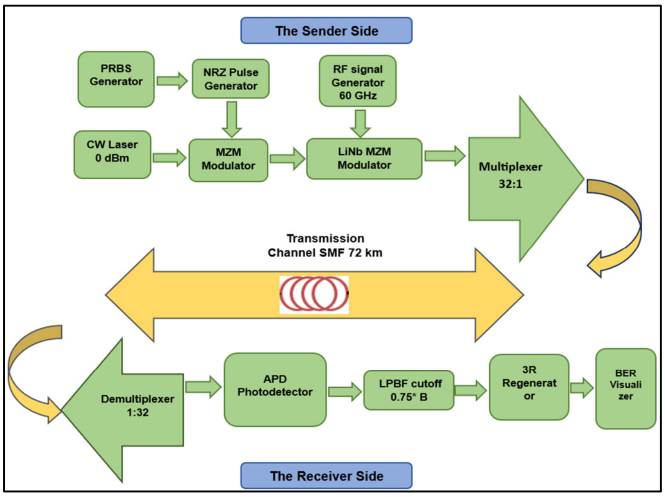


Fig. 2. Block diagram of the sender side, the receiver side, and the transmission channel between them.

The second part of the model is the optical channel, which consists of 72 km SMF 0.2 dB/km attenuation, and D =16.75 ps/nm/km dispersion coefficient. The optical beam of signals passes to the receiver side and is separated by a 1:32 demultiplexer. The third part of the model starts after the separation to acquire 32 channels (192-195.875 THz). Each channel carries an RF signal of 60 GHz, as portrayed in Figure 2. Each channel starts by converting the signal's optical form into an electrical form by an Avalanche Photo Detector (APD) with a gain of 8 dB followed by a Low Pass Bessel Filter (LPBF) operating with 0.75 times the bit rate of 10 Gbps to re-shape, re-filter, and re-generate the electrical signal by 3R to be displayed on the BER analyzer.

III. RESULTS AND DISCUSSION

The main goal of this work is to present the transmission mechanism of the 60 GHz radio signal carried by the192 THz optical signal across a maximum transmission distance of 72 km. The mechanism is examined to determine its efficiency and suitability to the limits of Q-factor and BER [21, 22]. The model was implemented with Optiwave version 7.0. The outcomes are presented in the BER analyzer to measure the opened eye diagram, the value of the Q-factor, and the BER. The operating power of the model is 0 dBm to bypass all linear and non-linear limitations in the optical transmission channel.

A. Results in Table Form

Each Table represents the relation between the Q-factor and the BER with varying transmission distances of 12, 22, 32, 42, 52, 62, and 72 km. The model was implemented with 8, 16, and 32 input channels, as displayed in Tables III-V [13]. It can be observed that the first 8 × 10 Gbps design (8 channels) surpassed the other two designs in the value of the Q-factor and the BER. The results demonstrte that the 8, 16, and 32- multi-channel model did not exceed the normal limits of the quality factor and BER (6 and E-9) after traveling the high distance of72 km.

TABLE III. Q-FACTOR AND BER FOR 8 DIFFERENT CHANNELS IN THE WDM-ROF MODEL VERSUS TRANSMISSION DISTANCE FOR 8 ×10 GBPS

Distance (km)	1st CH		3rd CH		6th CH		8th CH	
	Q-factor	BER	Q-factor	BER	Q-factor	BER	Q-factor	BER
12	30.7	1.8E-209	33.15	1.6E-241	34.3	1.4E-258	29.8	1.1E-213
22	25	1.7E-140	32.6	1.9E-184	28.06	6.2E-174	26.6	1.7E-160
32	20.02	1.5E-89	25.8	6.3E-116	20.6	7.5E-113	23.6	4.6E-115
42	15.2	2.3E-50	20.24	1.2E-59	16.8	2.8E-60	19.35	1.3E-83
52	9.95	1.1E-23	15.3	2.6E-35	13.4	8.8E-31	14.48	7.5E-51
62	8.5	2.1E-14	9.8	2.3E-15	9.1	2.1E-26	10.9	1.3E-24
72	6.8	2.9E-10	7.5	2.2E-11	7.8	2.2E-12	7.7	4.2E-12

TABLE IV. Q-FACTOR AND BER FOR 16 DIFFERENT CHANNELS IN THE WDM-ROF MODEL VERSUS TRANSMISSION DISTANCE FOR 16 ×10 GBPS

Distance (km)	1st CH		6th CH		11th CH		16th CH	
	Q-factor	BER	Q-factor	BER	Q-factor	BER	Q-factor	BER
12	28.8	1.8E-199	31.5	1.6E-205	30	1.4E-188	28.9	1.1E-208
22	23	1.7E-123	27.4	1.9E-143	25.7	6.2E-147	25.9	1.7E-165
32	17.7	1.5E-70	23	6.3E-99	19	7.5E-106	21.6	4.6E-115
42	12.7	2.3E-38	14.4	1.2E-47	16.6	2.8E-57	13.9	1.3E-63
52	8.8	1.1E-20	11.8	2.6E-27	11.4	8.8E-26	10.7	7.5E-48
62	7	2.1E-12	8.7	2.3E-14	8.8	2.1E-16	9.9	1.3E-31
72	5.6	2.9E-8	6.5	2.2E-10	6.8	2.2E-10	6.9	4.2E-11

TABLE V. Q-FACTOR AND BER FOR 23 DIFFERENT CHANNELS IN THE WDM-ROF MODEL VERSUS TRANSMISSION DISTANCE FOR 32 ×10 GBPS

Distance (km)	1st CH		16th CH		24th CH		32nd CH	
	Q-factor	BER	Q-factor	BER	Q-factor	BER	Q-factor	BER
12	27.2	1.8E-206	30.2	1.6E-230	28.5	1.4E-219	28.2	1.1E-189
22	21.7	1.7E-165	26.7	1.9E-192	23.2	6.2E-181	25.2	1.7E-129
32	15.4	1.5E-98	22.1	6.3E-109	18.6	7.5E-113	20.9	4.6E-85
42	11.8	2.3E-56	14.1	1.2E-47	15.7	2.8E-76	12.7	1.3E-53
52	7.4	1.1E-19	11.1	2.6E-29	10.75	8.8E-27	10.1	7.5E-39
62	6.4	2.1E-11	8.3	2.3E-17	8.1	2.1E-16	8.9	1.3E-21
72	5.4	2.9E-8	6.1	2.2E-11	6.3	2.2E-10	6.2	4.2E-10

B. Bit Error Rate and Q-Factor Relation with Distance

Each of the following Figures represents the relation between the Q-factor and the BER with transmission distance. The model was implemented with 8, 16, and 32 input channels.

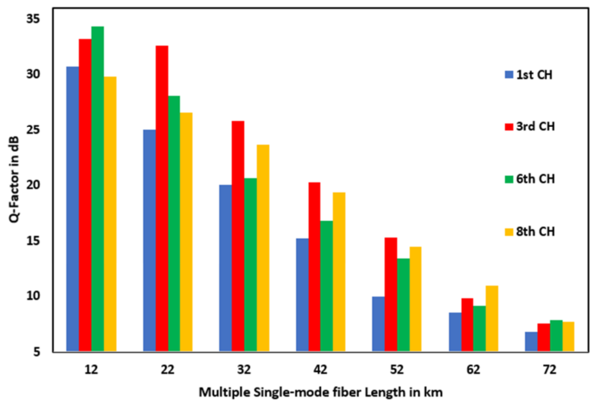


Fig. 3. Q-factor of 4 channels in the WDM-RoF model vs transmission distance for for 8 ×10 Gbps.

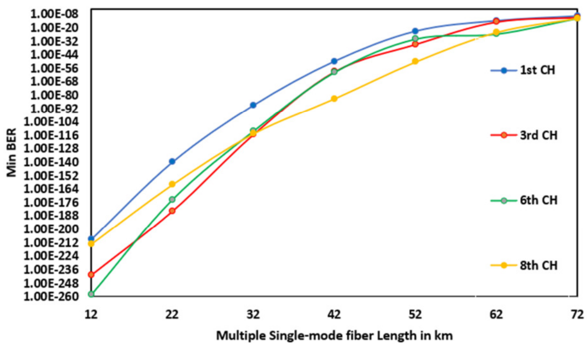


Fig. 4. Min BER of 4 channels in the WDM-RoF model vs the transmission distance for 8 ×10 Gbps.

As shown in Figures 3, 5, and 7, the Q-factor of the model with 8, 16, and 32 input channels produced enhancement upon the same model presented in [13] across all the values of the varying transmission distance. Figures 4, 6, and 8 represent the value of the minimal BER in the model evidenced in Figure 1 which exceeds the respective values of the same model introduced in [13]. On the one hand, the input channels were increased, which increased the coverage density of the RF signals, and results that do not exceed the nature of the Q-factor and the minimal BER were obtained.

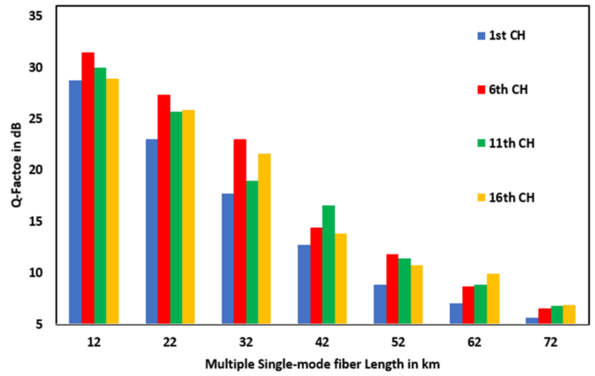


Fig. 5. Q-factor of 4 channels in the WDM-RoF model vs transmission distance for 16 ×10 Gbps.

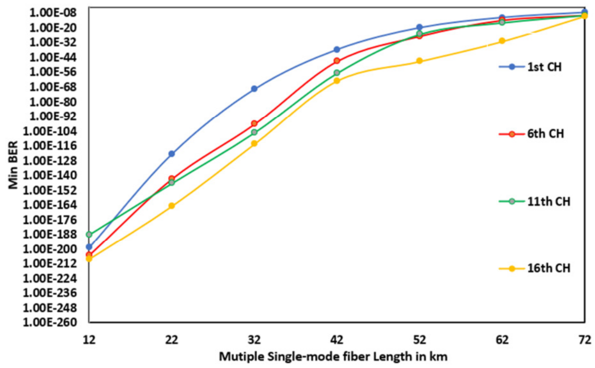


Fig. 6. Min BER of 4 channels in the WDM-RoF model vs the transmission distance for 16 ×10 Gbps.

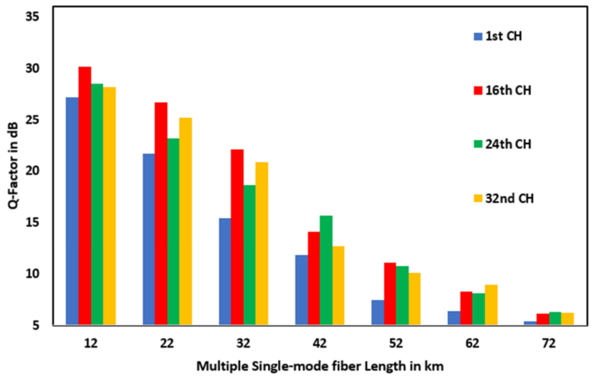


Fig. 7. Q-factor of 4 channels in the WDM-RoF model vs transmission distance for 32 ×10 Gbps.

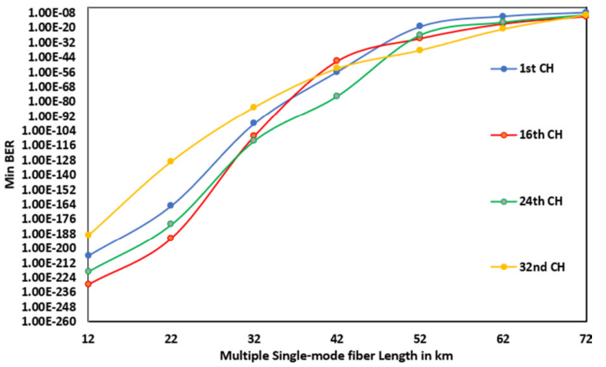


Fig. 8. Min BER of 4 channels in the WDM-RoF model vs the transmission distance for 32 ×10 Gbps.

C. Results in the Eye Diagram

Figures 9-11 illustrate the relation between the Q-factor and BER for a 72 km transmission distance and 8, 16, and 32 input channels.

IV. CONCLUSIONS

In this work, Optiwave version 7.0 was utilized to examine the performance of a 60 GHz mobile signal across a 72 km Single-Mode Fiber (SMF) link. The present study concentrated on Wavelength Division Multiplexing Radio over Fiber (WDM-RoF) systems that operated at 10 Gbps per channel and had 8, 16, and 32 channels. With coverage distances of up to 72 km, it was found that expanding the number of channels in the C-band (191.6 THz to 196 THz) improved the bit rate density and fortified the mobile signal.

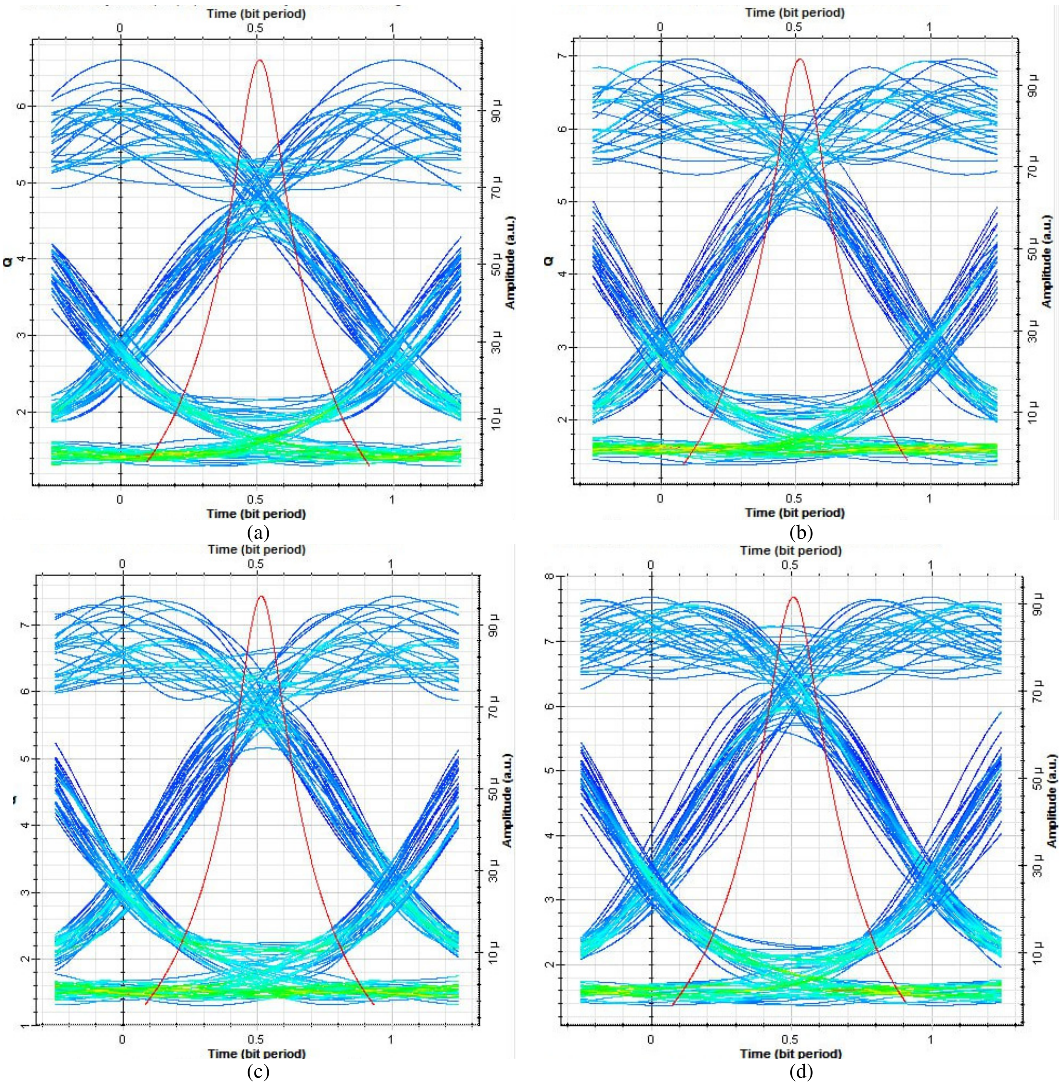
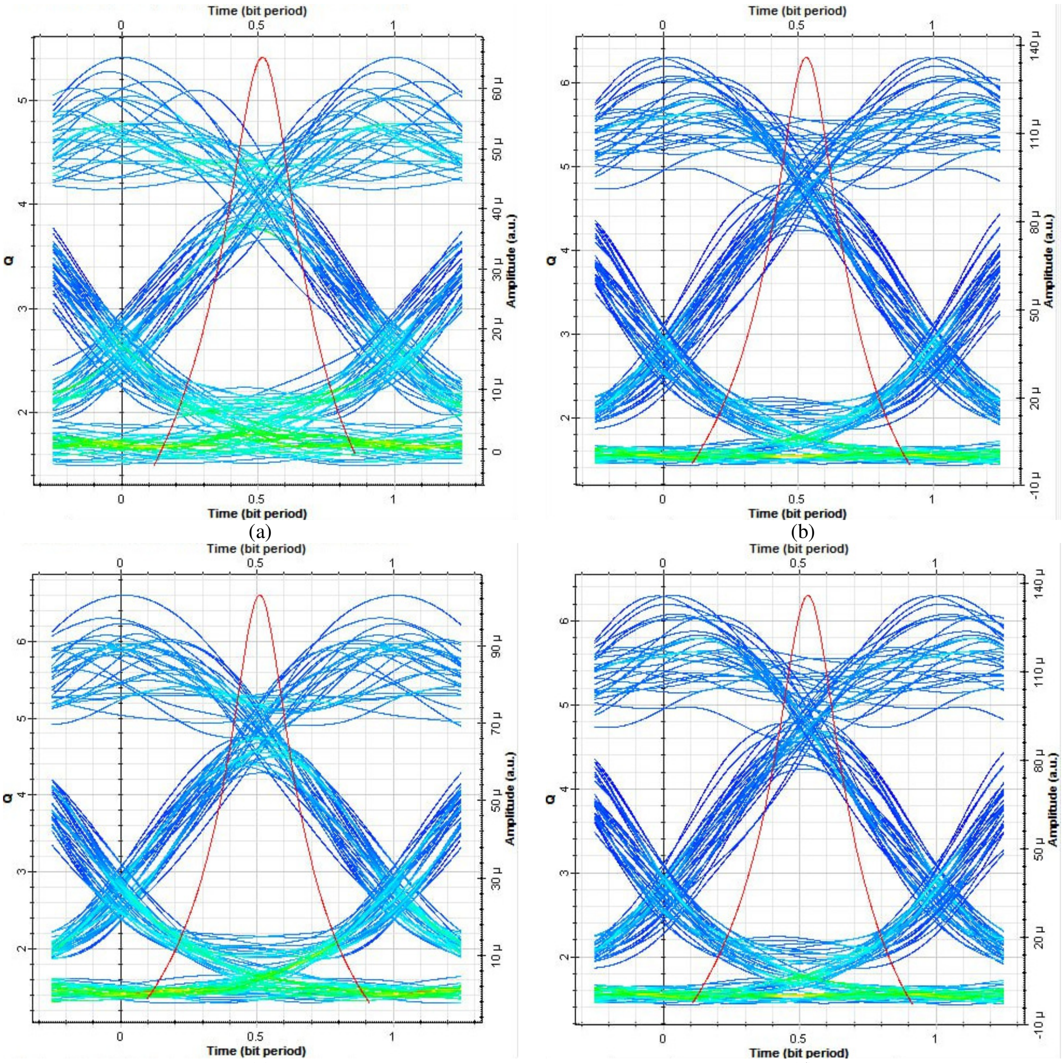


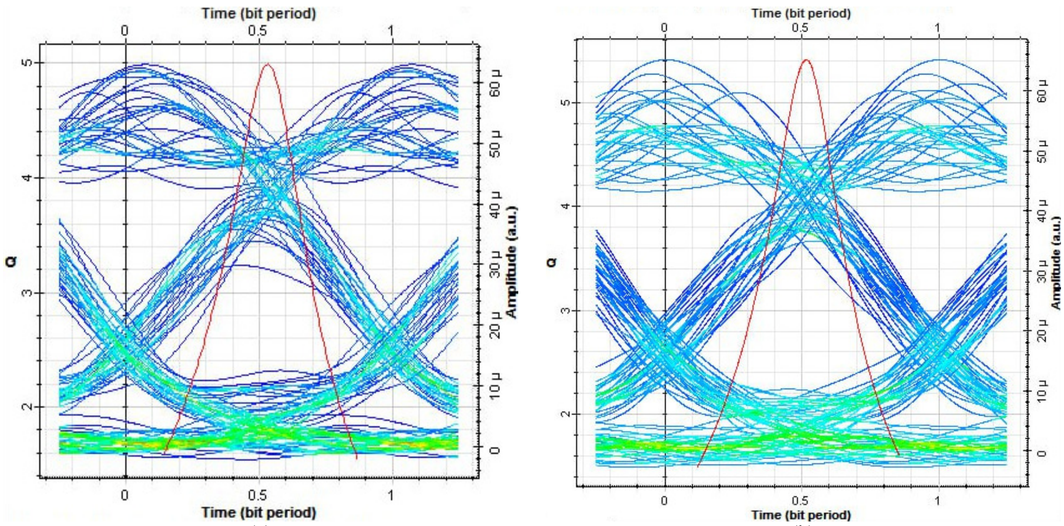
Fig. 9. Eye diagram of 4 different channels in the WDM-RoF model versus 72 km transmission distance for 8 ×10 Gbps: (a) 1st channel (192 THz), (b) 3rd channel (192.25 THz), (c) 6th channel (192.625 THz), and (d) 8th channel (192.875 THz).



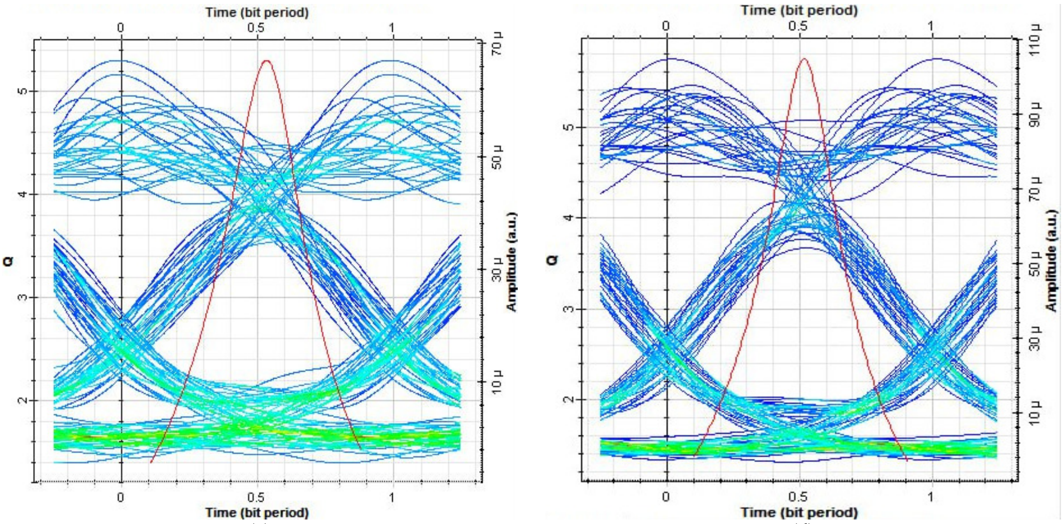
(a) (b)

(c) (d)

Fig. 10. Eye diagram of 4 different channels in the WDM-RoF model versus 72 km transmission distance for 16 ×10 Gbps: (a) 1st channel (192 THz), (b) 6th channel (192.625 THz), (c) 11th channel (193.375 THz), and (d) 16th channel (193.875 THz).



(a) (b)



(c) (d)

Fig. 11. Eye diagram of 4 different channels in the WDM-RoF model versus 72 km transmission distance for 32 ×10 Gbps: (a) 1st channel (192 THz), (b) 16th channel (193.875 THz), (c) 24th channel (194.875 THz), and (d)32th channel (195.875 THz).

It was observed that system performance measurements, like Q-factor and minimal Bit Error Rate (BER), exhibited a discernible decrease as the number of channels increased.

The novelty of this work lies in the thorough analysis of WDM-RoF systems with a large number of channels (up to 32) and the evaluation of the way they function over a big fiber length of 72 km, in contrast to other works that investigated various technologies and configurations to improve the RoF system performance.

This study offers a thorough assessment of system performance indicators across various channel configurations, including the BER and Q-factor. In the 8-channel WDM-RoF model, Q-factors of 6.8, 7.5, 7.8, and 7.7 were obtained with corresponding minimal BER values of 2.9E-10, 2.2E-11, 2.2E-12, and 4.2E-12, at an aggregate data rate of 80 Gbps. The system's minimal BERs were 2.9E-8, 2.2E-10, 2.2E-10, and 4.2E-11, while its Q-factors were 5.6, 6.5, 6.8, and 6.9 as it expanded to 16 channels (160 Gbps). A further increase to 32 channels (320 Gbps) produced minimal BERs of 2.9E-8, 2.2E-11, 2.2E-10, and 4.2E-10, as well as Q-factors of 5.4, 6.1, 6.3, and 6.2.

These results demonstrate the trade-offs between preserving signal integrity across long fiber distances and expanding the number of channels. The current work highlights the significance of the tuning system settings to balance the bit rate density and signal quality and offers insightful information on the scalability of WDM-RoF systems. Future research attempting to improve the performance of high-capacity fiber-optic communication systems can use this work as a reference.

REFERENCES

[1] N. C. Eli-Chukwu, J. M. Aloh, and C. O. Ezeagwu, "A Systematic Review of Artificial Intelligence Applications in Cellular Networks," *Engineering, Technology & Applied Science Research*, vol. 9, no. 4, pp. 4504–4510, Aug. 2019, https://doi.org/10.48084/etasr.2788.

[2] A. N. Uwaechia and N. M. Mahyuddin, "A Comprehensive Survey on Millimeter Wave Communications for Fifth-Generation Wireless Networks: Feasibility and Challenges," *IEEE Access*, vol. 8, pp. 62367–62414, Jan. 2020, https://doi.org/10.1109/ACCESS.2020.2984204.

[3] F. Kareem *et al.*, "A Survey of Optical Fiber Communications: Challenges and Processing Time Influences," *Asian Journal of Computer Science and Information Technology*, vol. 7, no. 4, pp. 48–58, Apr. 2021, https://doi.org/10.9734/AJRCOS/2021/v7i430188.

[4] A. Munadel and E. kadhum Hamza, "Simulation and Analysis of the OFDM Transceiver Based Commutation System," *Journal of Engineering*, vol. 26, no. 12, pp. 131–140, Dec. 2020, https://doi.org/10.31026/j.eng.2020.12.08.

[5] A. E. Ibhaze, F. O. Edeko, and P. E. Orukpe, "A Signal Amplification-based Transceiver for Visible Light Communication," *Journal of Engineering*, vol. 26, no. 11, pp. 123–132, Nov. 2020, https://doi.org/10.31026/j.eng.2020.11.08.

[6] D. E. Mohsen, A. M. Hammadi, and A. J. Alaskary, "Design and Implementation of 1.28 Tbps DWDM based RoF system with External Modulation and Dispersion Compensation Fiber," *Journal of Physics: Conference Series*, vol. 1963, Jul. 2021, Art. no. 012026, https://doi.org/10.1088/1742-6596/1963/1/012026.

[7] H. A. W. Jabori and O. A. L. A. Ridha, "Simple 2D chaotic remapping scheme for securing optical communication networks," *Journal of Engineering*, vol. 25, no. 12, pp. 85–95, Nov. 2019, https://doi.org/10.31026/j.eng.2019.12.07.

[8] H. A. Mohammed and H. J. Kbashi, "Transmission of a multiplexed eight channels subcarrier optically intensity modulated based on microcontroller," *Journal of Engineering*, vol. 15, no. 2, pp. 3633–3640, Jun. 2009, https://doi.org/10.31026/j.eng.2009.02.09.

[9] M. M. A. Eid, S. El-Meadawy, A. E.-N. A. Mohammed, and A. N. Z. Rashed, "Wavelength division multiplexing developed with optimum length-based EDFA in the presence of dispersion-compensated fiber system," *Journal of Optical Communications*, vol. 45, no. s1, pp. s293–s303, Jun. 2024, https://doi.org/10.1515/joc-2020-0302.

[10] S. Ilic, B. Jaksic, M. Petrovic, A. Markovic, and V. Elcic, "Analysis of Video Signal Transmission Through DWDM Network Based on a Quality Check Algorithm," *Engineering, Technology & Applied Science Research*, vol. 3, no. 2, pp. 416–423, Apr. 2013, https://doi.org/10.48084/etasr.293.

[11] B. J. Puttnam, G. Rademacher, and R. S. Luís, "Space-division multiplexing for optical fiber communications," *Optica*, vol. 8, Sep. 2021, Art. no. 1186, https://doi.org/10.1364/OPTICA.427631.

[12] M. Seifouri, M. M. Karkhanehchi, and S. Rohani, "Design of Multi-Layer Optical Fibers with Ring Refractive Index to Reduce Dispersion and Increase Bandwidth in Broadband Optical Networks," *Engineering,*

Technology & Applied Science Research, vol. 2, no. 3, pp. 216–220, Jun. 2012, https://doi.org/10.48084/etasr.166.

[13] A. S. Elgamal, O. Z. Aletri, B. A. Yosuf, A. Adnan Qidan, T. El-Gorashi, and J. M. H. Elmirghani, "AI-Driven Resource Allocation in Optical Wireless Communication Systems," in *23rd International Conference on Transparent Optical Networks*, Bucharest, Romania, Jul. 2023, pp. 1–5, https://doi.org/10.1109/ICTON59386.2023.10207473.

[14] D. Jain and B. Iyer, "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*, vol. 14, no. 3, pp. 746–758, Jul. 2023, https://doi.org/10.1007/s13198-020-01051-1.

[15] G. Pandey, A. Choudhary, and A. Dixit, "Wavelength Division Multiplexed Radio Over Fiber Links for 5G Fronthaul Networks," *IEEE Journal on Selected Areas in Communications*, vol. 39, no. 9, pp. 2789–2803, Sep. 2021, https://doi.org/10.1109/JSAC.2021.3064654.

[16] L. M. Younis and E. Essa, "Multi-Channel of High Speed Optical Network Based RoF/WDM Architecture," *Journal of Advanced Sciences and Nanotechnology*, vol. 2, no. 1, pp. 188–203, Apr. 2023, https://doi.org/10.55945/joasnt.2023.2.1.188–203.

[17] H. Al-Yasiri, I. Al-Hussaini, and S. Al-Ani, "Design and Analysis of Enhanced Performance Simulator for GSM Network," *Journal of Engineering*, vol. 11, no. 2, pp. 339–360, Jun. 2005, https://doi.org/10.31026/j.eng.2005.02.09.

[18] H. Yang *et al.*, "10-W power light co-transmission with optically carried 5G NR signal over standard single-mode fiber," *Optics Letters*, vol. 46, no. 20, pp. 5116–5119, Oct. 2021, https://doi.org/10.1364/OL.441940.

[19] T. P. Okoumassoun, A. Antwiwaa, and N. K. Gerrar, "Performance Evaluation of Optical Amplifiers in a Hybrid RoF-WDM Communication System," *Journal of Communications*, vol. 18, no. 8, pp. 522–536, Aug. 2023, https://doi.org/10.12720/jcm.18.8.522-536.

[20] D. S. Jain and B. Iyer, "Design and Analysis of Single-Channel High-Speed RoF System Using Different Coding Techniques," in *6th International Conference on Communication and Information Processing*, Tokyo, Japan, Nov. 2020, pp. 1–9.

[21] D. Garg and A. Nain, "An efficient 110 × 8 GHz WDM RoF system design for 5G and advance wireless networks," *Optical and Quantum Electronics*, vol. 54, no. 6, May 2022, Art. no. 342, https://doi.org/10.1007/s11082-022-03726-4.

[22] D. Jain and B. Iyer, "Design and Analysis of 8-Channel WDM-RoF Using the C and L Band for 5G and Beyond Applications," *International Journal of Engineering Trends and Technology*, vol. 71, no. 1, pp. 41–52, Jan. 2023, https://doi.org/10.14445/22315381/IJETT-V71I1P205.

[23] A. Sharma, S. Chaudhary, D. Thakur, and V. Dhasratan, "A Cost-Effective High-Speed Radio over Fibre System for Millimeter Wave Applications," *Journal of Optical Communications*, vol. 41, no. 2, pp. 177–180, Apr. 2020, https://doi.org/10.1515/joc-2017-0166.

[24] M. Ahmed and M. Yamada, "Effect of intensity noise of semiconductor lasers on the digital modulation characteristics and the bit error rate of optical communication systems," *Journal of Applied Physics*, vol. 104, no. 1, Jul. 2008, Art. no. 013104, https://doi.org/10.1063/1.2949275.

[25] T. Ivaniga and P. Ivaniga, "Evaluation of the bit error rate and Q-factor in optical networks," *IOSR Journal of Electronics and Communication Engineering*, vol. 9, no. 6, pp. 1–4, 2014, https://doi.org/10.9790/2834-09610103.