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Design and Performance Analysis of 32-Channels WDM-RoF System

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The growing demand for high-speed, long-distance communication has been growing exponentially. This growth is fueled by the increasing need for faster data transfer rates and enhanced network capabilities to support modern applications such as 5G, IoT, and high-definition streaming services. As a result, the use of Wavelength Division Multiplexing (WDM) in Fiber Optic (FO) offers several benefits, including increased capacity, higher bit rates. Radio over Fiber (RoF) systems are particularly promising for 5G networks due to their ability to deliver the necessary bandwidth for broadband data transmission to end-users. The received RoF signal degradation over long distances leads to high Bit Error Rates (BER) and low Q-factor values, affecting network performance. To address these problems, we proposed a 32-channel WDM-based RoF system using Optical Phase Conjugator (OPC) and Fiber Bragg Grating (FBG) for dispersion compensation. The system is evaluated in Optisystem 19.0 tool over transmission distances of 60 km, 120 km, 180 km and 240 km, with channel spacings of 0.5 nm. Optimal results were achieved at 0 dBm CW laser power, maintaining a Q-factor above 6 and BER below 10^{-9}. The results demonstrate an efficient high-performance system capable of achieving 320 Gbps data transmission.

Keywords: RoF, Opti system, Wavelength division multiplexing, WDM-RoF, Fiber bragg grating, Optical phase conjugator

1 Introduction

Optical fiber communication allows multiple signals to travel simultaneously using different wavelengths within a single fiber[1]. A key technology in optical fiber communication is Wavelength Division Multiplexing (WDM)[2]. WDM is widely used in telecommunications, especially in the low-loss 1300-1600 nm spectral range, to maximize data transmission efficiency while minimizing interference[3].

Fiber-optic communication systems are primarily composed of key components, including light sources such as Light Emitting Diodes (LEDs) or LASERs, optical fibers as transmission media, photodetectors (such as silicon-based detectors), and essential electronic hardware for signal processing. To maintain signal integrity an Erbium-Doped Fiber Amplifier (EDFA) is an optical amplifier that boosts optical signals using a doped fiber as a gain medium[4]. It provides a wide gain bandwidth, reducing system complexity and improving reliability, especially in WDM systems[5]. They are widely used in C-band and L-band regions to enhance signal strength while maintaining high data transmission rates[6].

Radio over Fiber (RoF) enhances wireless communication by transmitting RF signals over fiber, making it ideal for mobile networks. RoF architecture connecting a central station to multiple Radio Access Points[7] via optical fiber to meet growing bandwidth demands in indoor and outdoor applications[8]. Raman amplifiers enhance optical signals using Stimulated Raman Scattering (SRS) and are key in WDM systems[9-10]. They work across various optical bands, including C and L bands, to boost signal strength[11] and transmission capacity[12]. To further improve the efficiency of optical transmission[13], electro-optic devices such as Mach-Zehnder Modulators (MZMs) are employed for modulating optical signals[14]. MZMs enable precise control over the amplitude, phase, and frequency of optical signals, making them essential for advanced communication systems. A MZM is an electro-optic device used to modulate the amplitude, phase, or frequency of an optical signal based on an applied electrical signal depicts in Fig. 1[15,16].

Optical Phase Conjugators (OPCs) mitigate signal distortions by generating a phase-inverted replica of the optical signal, effectively counteracting dispersion and nonlinear effects over long transmission distances. Fiber Bragg Gratings (FBG) offer precise wavelength control[17], providing effective dispersion compensation[18] and reducing signal degradation in optical communication systems[19]. The central

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wavelength (or Bragg wavelength) that is reflected by the grating is given by[20].

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

where, η_{ef} is the core effective index, and Λ is the grating period[20].

2 Simulation Setup

The proposed 32-channel WDM-RoF network is simulated using OptiSystem software. It utilizes LASERs operating at a reference wavelength of 1550 nm with a channel spacing of 0.5 nm, as shown in Fig. 2.

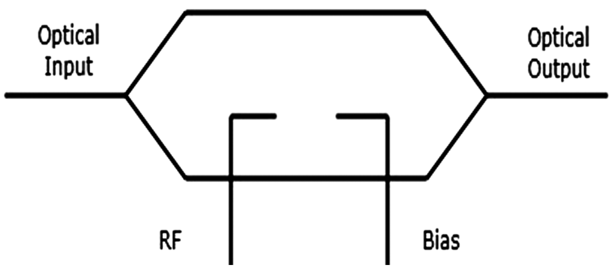

Fig. 1 — Layout of the MZM[7]

Table 1 provides a detailed overview of the key parameters and their corresponding values used in simulating the proposed WDM-RoF system.

The conceptual block diagram is shown in Fig. 2. It demonstrates the arrangement of transmitter receiver

Table1 — Wavelength utilization in proposed system corresponding to each channel

Channel Number	Wavelength (nm)	Channel Number	Wavelength (nm)
Channel 1	1550	Channel 17	1558
Channel 2	1550.5	Channel 18	1558.5
Channel 3	1551	Channel 19	1559
Channel 4	1551.5	Channel 20	1559.5
Channel 5	1552	Channel 21	1560
Channel 6	1552.5	Channel 22	1560.5
Channel 7	1553	Channel 23	1561
Channel 8	1553.5	Channel 24	1561.5
Channel 9	1554	Channel 25	1562
Channel 10	1554.5	Channel 26	1562.5
Channel 11	1555	Channel 27	1563
Channel 12	1555.5	Channel 28	1563.5
Channel 13	1556	Channel 29	1564
Channel 14	1556.5	Channel 30	1564.5
Channel 15	1557	Channel 31	1565
Channel 16	1557.5	Channel 32	1565.5

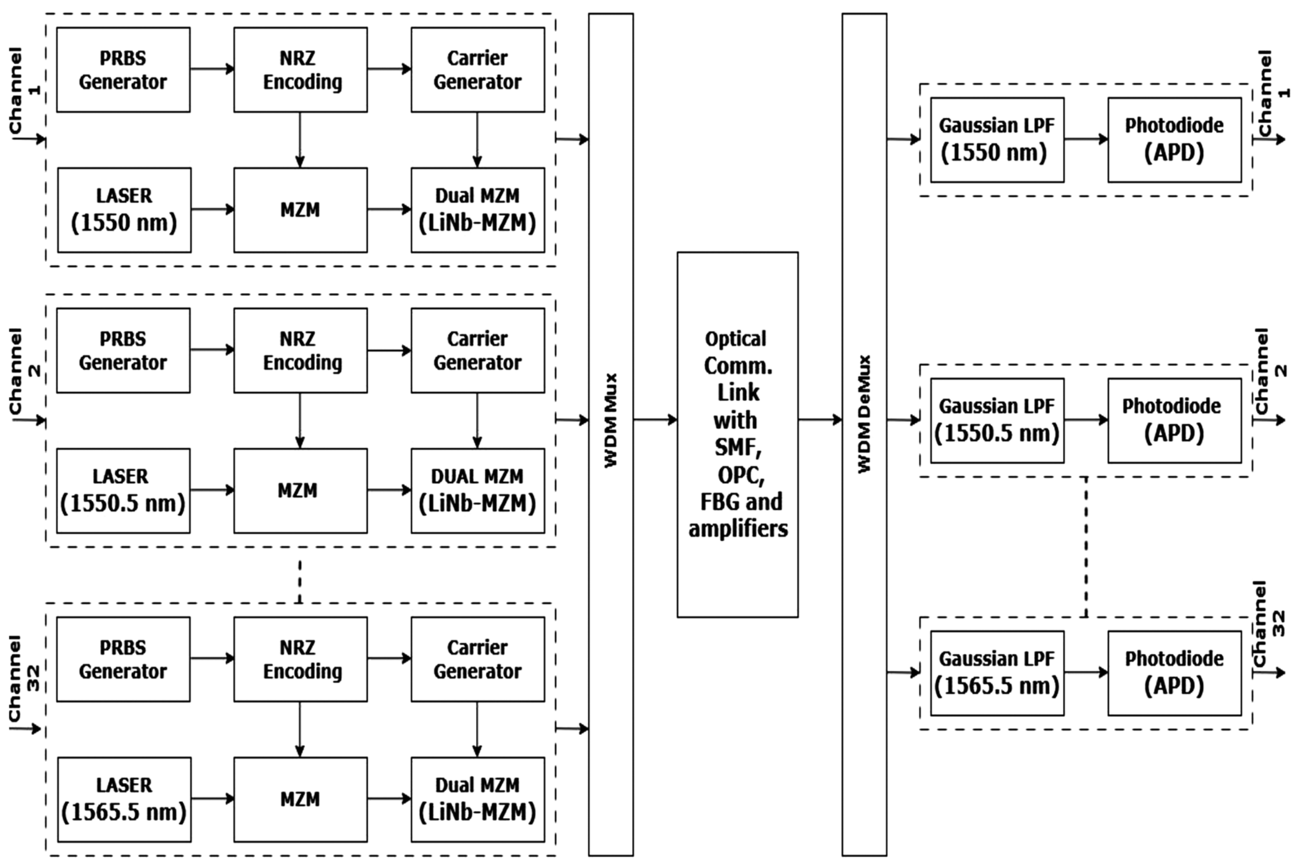

Fig. 2 — Conceptual diagram of proposed 32-channel system

and transmission channel. In the channel, we have utilized some advance technology components like OPC, FBG along with amplifiers.

The proposed WDM-RoF system is made up of two main parts: the transmitter and the receiver, as shown in Figs. 3 and 4. Figure 5 depicts the simulation setup of proposed system.

The transmitter uses a LASER source that emits light at a wavelength of 1550 nm. This light is then modulated using a pair of MZMs, specifically LiNb-MZMs, which are ideal for high-speed and high-bandwidth signal modulation.

Once modulated, the signal travels through optical fiber cables over distances ranging from 60 km to

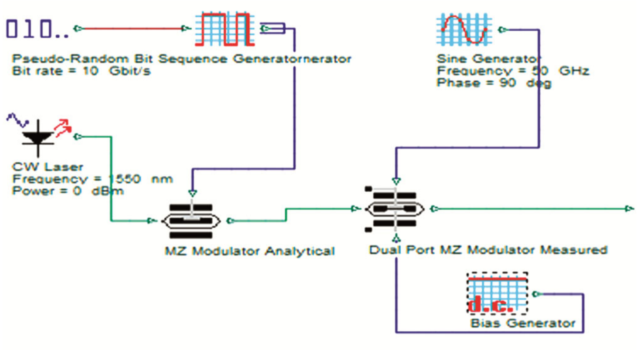

Fig. 3 — Transmitter part

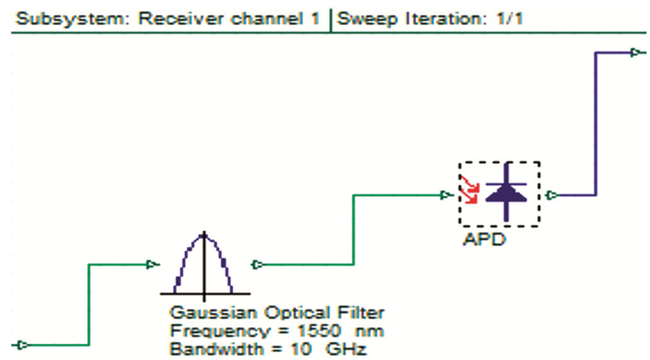

Fig. 4 — Receiver part

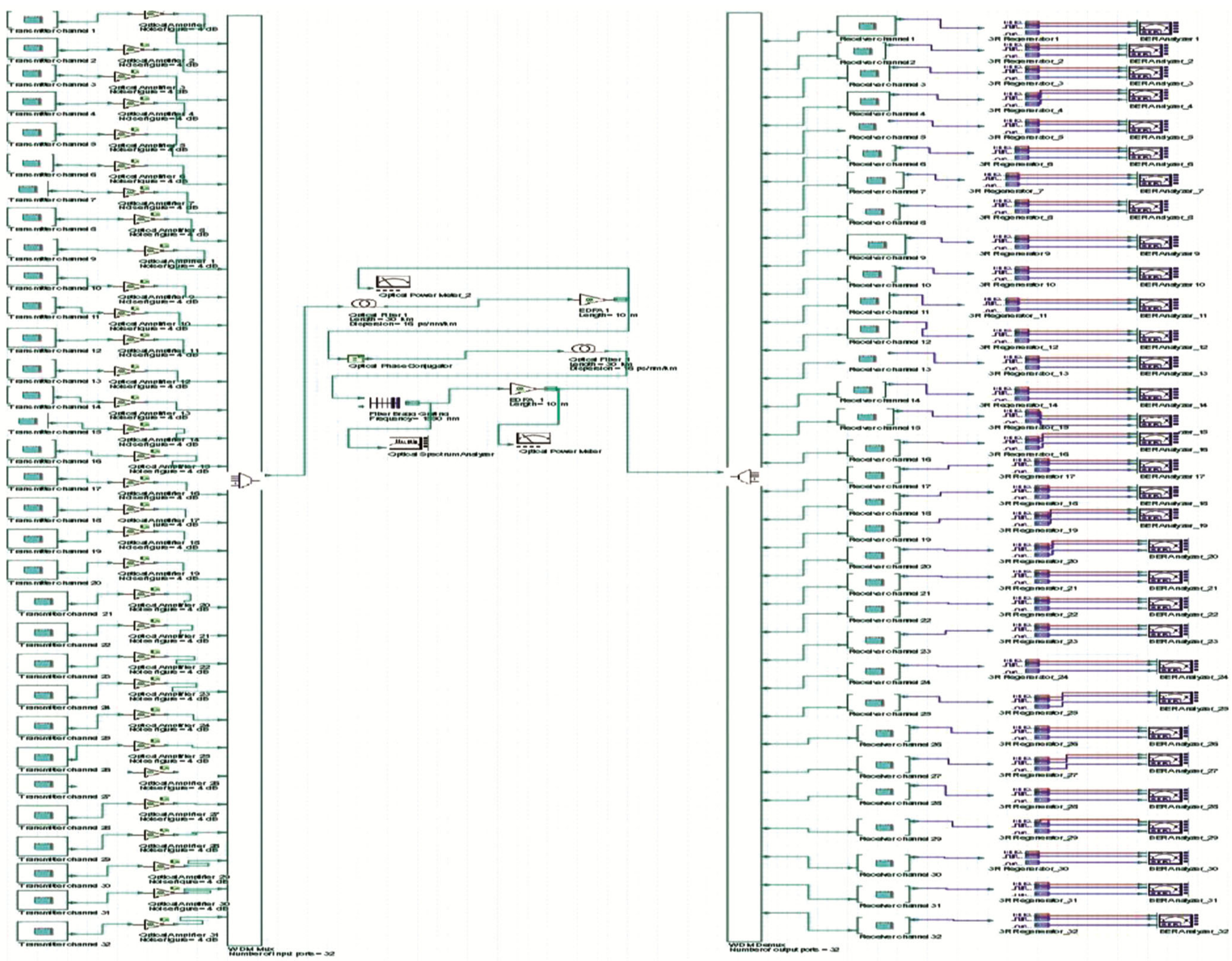

Fig. 5 — Simulation setup of proposed 32-channel system

240 kms, channel layout shown in Fig. 6. To keep the signal clear and strong over long distances, OPC and FBG are placed along the fiber links (Fig. 6).

At the receiving end, an Avalanche Photodiode (APD) detects the incoming optical signal. Meanwhile, FBG acts as a filter, reflecting specific wavelengths while allowing others to pass through, which improves overall signal stability. Together, these technologies enhance the performance of the system, ensuring reliable and efficient data transmission over long distances. To mitigate the non-linearities in photodiode different optimization technologies can also be used along withthis setup.

3 Results and Discussion

The simulated results of the WDM-RoF system were analyzed to assess key performance metrics, particularly the impact of BER and Q-factor. The evaluation covered distances up to 240 km, providing valuable insights into the system's efficiency over long-range communication.

The simulation tested signal propagation across distances from 60 km to 240 km for 32-channels, each operating at wavelengths between 1550 nm and 1565.5 nm with a spacing of 0.5 nm.

With a data rate of 10 Gbps and a radio signal frequency of 50 GHz, the system's performance was thoroughly evaluated, and the results are presented in the following graphs Figs. 7 and 8.

3.1 BER analysis

The simulation results highlight the performance of the proposed 32-channel WDM-RoF system over varying transmission distances. The value of BER for channel 32 (1565.5 nm) is 1.20*1e-11, 1.12*1e-10, 1.07*1e-09 and 1.04*1e-09 at distances 60 km, 120 km, 180 km and 240 km respectively. In the Fig. 7, the different values of observed BER with respect to each channel of 32-channels.

This degradation in signal quality with greater distances is expected due to factors such as attenuation and dispersion. These findings emphasize the significance of careful planning and signal optimization strategies for long-distance WDM-RoF systems

3.2 Q-factor analysis

The simulation results represent the performance of the proposed 32-channel WDM-RoF system over

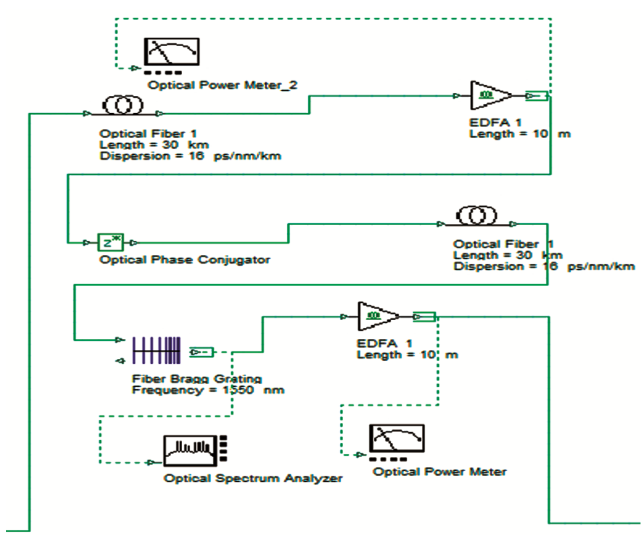

Fig. 6 — Transmission channel layout

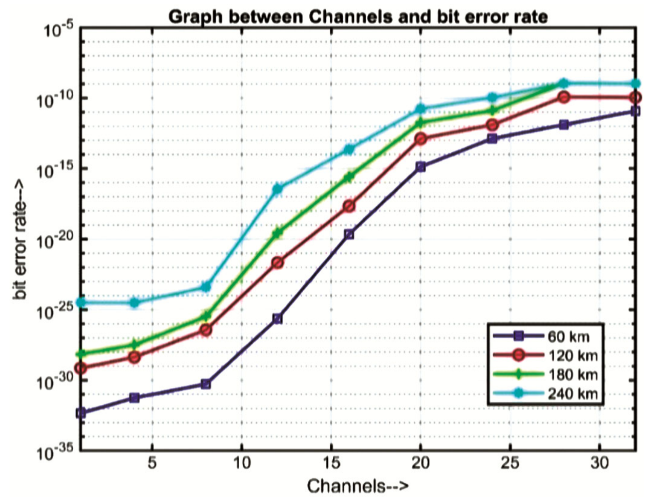

Fig. 7 — Graph between channels and bit Error rate

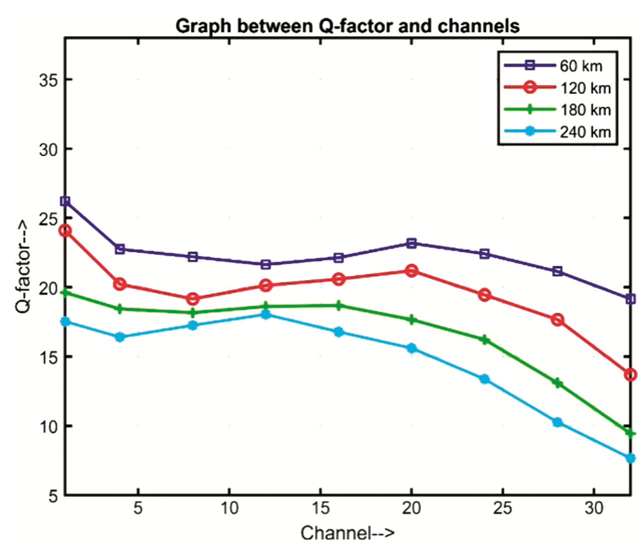

Fig. 8 — Graph between channels and Q-factor

varying transmission distances. The value of Q-factor for channel 32 (1565.5 nm) is 19.16 at 60 km, 13.70 at 120 km, 9.45 at 180 km, and 7.67 at 240 km. The analysis underscores the performance of the designed system, consistently ensuring high-quality transmission with value of Q-factor above 6 across all 32-channels within the transmission distance range of 60 km to 240 kms, as depicts in Fig. 8.

The simulation results show that the minimum Q-factor for channel 32 decreases with increasing transmission distance due to dispersion and attenuation. The observation highlights the importance of addressing these challenges to maintain reliable and efficient data transmission over extended distances.

Both the (BER and Q-factor) results show that system's performance drops at higher wavelengths. This happens due to fiber nonlinear effects like Kerr and Raman scattering, which cause signal interference at high

4 Conclusion

This paper proposes a WDM-RoF system optimized for high-speed data transmission. Wavelength Division Multiplexing and advanced modulation techniques have emerged as key solutions to meet the growing demand of users. However, signal degradation over long distances remains a major challenge, leading to increased BER and reduced Q-factor values, which can impact high-speed data transmission.

We proposed a 32-channel WDM-based RoF system, integrates OPC and FBG for effective dispersion compensation. Performance is evaluated over transmission distances of 60 km, 120 km, 180 and 240 kms. Our model successfully achieved a total data transmission rate of 320 Gbps, demonstrating its potential for high-speed communication systems.

The results show that the value of Q-factor for channel 32 remains above 6, while the BER remains 10^{-9}, confirming the system's ability to maintain reliable performance over large distance of 240 kms.

Overall, the proposed 32-channel WDM-RoF system presents a promising solution for diverse communication applications, offering enhanced transmission efficiency and reliability. The system demonstrates promising results for 5G applications.

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