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RESEARCH ARTICLE

Performance Analysis of 8 × 112 Gbps (0.896 Tbps) WDM ROF Link Using 32 QAM – OFDM Modulation Scheme for Achieving Extended Range

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Abstract: We propose an advanced optical transport system utilizing higher order modulation formats and coherent detection. Our innovation introduces an 8 × 112 Gbps wavelength division multiplexing – radio over fiber (WDM ROF) link using a 32 quadrature amplitude modulation-orthogonal frequency division (QAM-OFDM) modulation scheme, capable for extending its reach. Our proposed research stands out from existing studies due to its distinctive use of the 32-QAM format and a 112 Gbps data rate per channel, especially when considering a channel span of 3000 km. Our analysis covers WDM-ROF link systems, including a preoptical amplifier within the link, one optical amplifier outside the channel loop span, and one within the loop span, representing distinct scenarios. We operated optical amplifiers in the gain-controlled mode. Remarkably, exclusive of employing precise dispersion or nonlinearity improvement techniques, carried out simulations reveal optimal transmission distance for our anticipated system having considered specification parameters is 3000 Km. We conducted extensive simulations to assess the system performance in terms of quality factor (Q-factor), estimated symbol error (ESE), and error vector magnitude (EVM) over link spans ranging from 1000 to 15,000 km.

Keywords: wavelength division multiplexing (WDM), quadrature amplitude modulation (QAM), orthogonal frequency division multiplexing (OFDM), estimated symbol error (ESE), error vector magnitude (EVM), quality factor (Q-factor)

1. Introduction

To meet the escalating traffic demands, there is a constant need for copious data rates on each individual channel in multichannel wavelength division multiplexing (WDM)-based radio over fiber (ROF) systems. This is essential to support bandwidth-intensive applications. For achieving higher spectral density and enabling high-speed, long-distance transmission in WDM systems, it is advisable to transmit data using symbols containing two or more bits, as recommended in reference [1–4]. M-ary quadrature amplitude modulation methods like 8 QAM, 16 QAM, 32 QAM, and 64 QAM used with orthogonal frequency division multiplexing are the best option for meeting the current and future needs of data-rate hungry applications.

Nonlinearity and dispersion are fundamental properties of optical fibers that pose significant challenges for designing long-distance WDM optical communication systems [5]. To improve the performance of long-distance WDM optical communication systems, it is necessary to suppress and mitigate bottlenecks such as dispersion and nonlinearity. This can be done by using coherent detection systems with dispersion compensating fibers, suitable digital back-propagation techniques, and preequalization techniques [1, 6–10]. Leveraging optical amplifiers (OAs) in various configurations within a recirculating loop, coupled with the utilization of a QAM-OFDM modulation format and coherent detection at the receiver, represents a technologically advanced approach to enable high-data-rate, long-distance communication systems (emerging research suggests that digital signal processing (DSP)) can be used offline to improve the performance of WDM ROF systems with different m-ary QAM-OFDM modulation schemes for long-distance transmission at terabit-per-second data rates [5]. The rest of the paper is organized as follows: Section 2 presents the proposed system design, including: A general block diagram of an 8-channel WDM ROF system, inside views of the transmitter section, A fiber span with one optical preamplifier, two OAs inside the channel span, and the receiver section. Section 3 illustrates the results and discussion, and Section 4 presents the conclusion.

2. System Design

In our proposed work, we designed and simulated an eight-channel WDM ROF system by means of 32QAM-OFDM modulation, with each channel operating at a data rate of 112

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Gbps, resulting in a total data rate of 0.896 terabit-per-seconds. The system performance tested over a transmission link span of up to 15,000 Kms.

Our study aligns with prior research, highlighting that highly spaced subcarriers enhance system performance by reducing the Q penalty, although at the expense of spectral efficiency [11]. The Q penalty is a measure of the degradation in the performance of a communication system due to noise. It is typically expressed in decibels (dB). A higher Q penalty means that more noise present in the system, which can lead to errors in data transmission. In the context of QAM-OFDM, the Q penalty can be caused by inter-symbol interference (ISI) and inter-carrier interference (ICI). ISI occurs when the symbols of a transmitted signal overlap in time, while ICI occurs when the subcarriers of a transmitted signal overlap in frequency [1, 4, 7, 12]. In general, highly spaced subcarriers are less susceptible to interference from neighboring subcarriers. This means that the Q penalty is lower, and the system performance is better. However, the spectral efficiency of the system is also lower, because more space is required between the subcarriers. We have also explored the effectiveness of digital back propagation (DBP) and pilot-aided techniques in coherent optical communication systems using the QAM-OFDM format, showing reliable results up to 4000 km, even at 112 Gbps per channel, similar to dispersion-managed links [13].

Additionally, we have considered other relevant studies, such as a WDM optical system utilizing PM-DQPSK signals for a 100 Gbps data rate over a 2700-kilometer transmission distance [14, 15]. We have also touched upon the transmission of DC-DQPSK/DP-QPSK signals over 1000 km, co-propagating with 10.7 Gbps OOK signals in long-distance WDM optical systems [16].

Our main contribution lies in estimating the performance of our 8-channel WDM ROF system, operating at 896 Gbps using the QAM-OFDM modulation format. We have conducted simulations covering various scenarios, including the presence of preoptical amplifiers, external OAs, and amplifiers within the channel and recirculated loop spans. These simulations span transmission distances from 1000 to 15,000 km, with an iterative loop channel concept employed to achieve the longer span. Detailed system and single-mode fiber (SSMF) cable specifications are provided in Tables 1 and 2 for reference.

Table 1
Specifications of fiber cable

Parameters considered	Parameter's values
Type of fiber	SSMF
Fiber attenuation loss	0.2 (dB/Km)
Amount of dispersion	16.75 (ps/nm/Km)
Slop of dispersion	0.075 (ps/nm^2/k)
Effective area	80 (μm^2)
Coefficient of nonlinearity	1.31 (W^{-1} m^{-1})
Channel span length	1000 to 15,000 (Kms)

Table 2
Specifications of proposed system

Parameter considered	Parameter's values
Data rate	112 Gbps (per channel)
Reference wavelength	1550 (nm)
Input power level	0 (dBm)
Sequence length	32,768 (bits)
Types of modulation	32 QAM-OFDM
WDM channel numbers	8

2.1. Transmitter section design

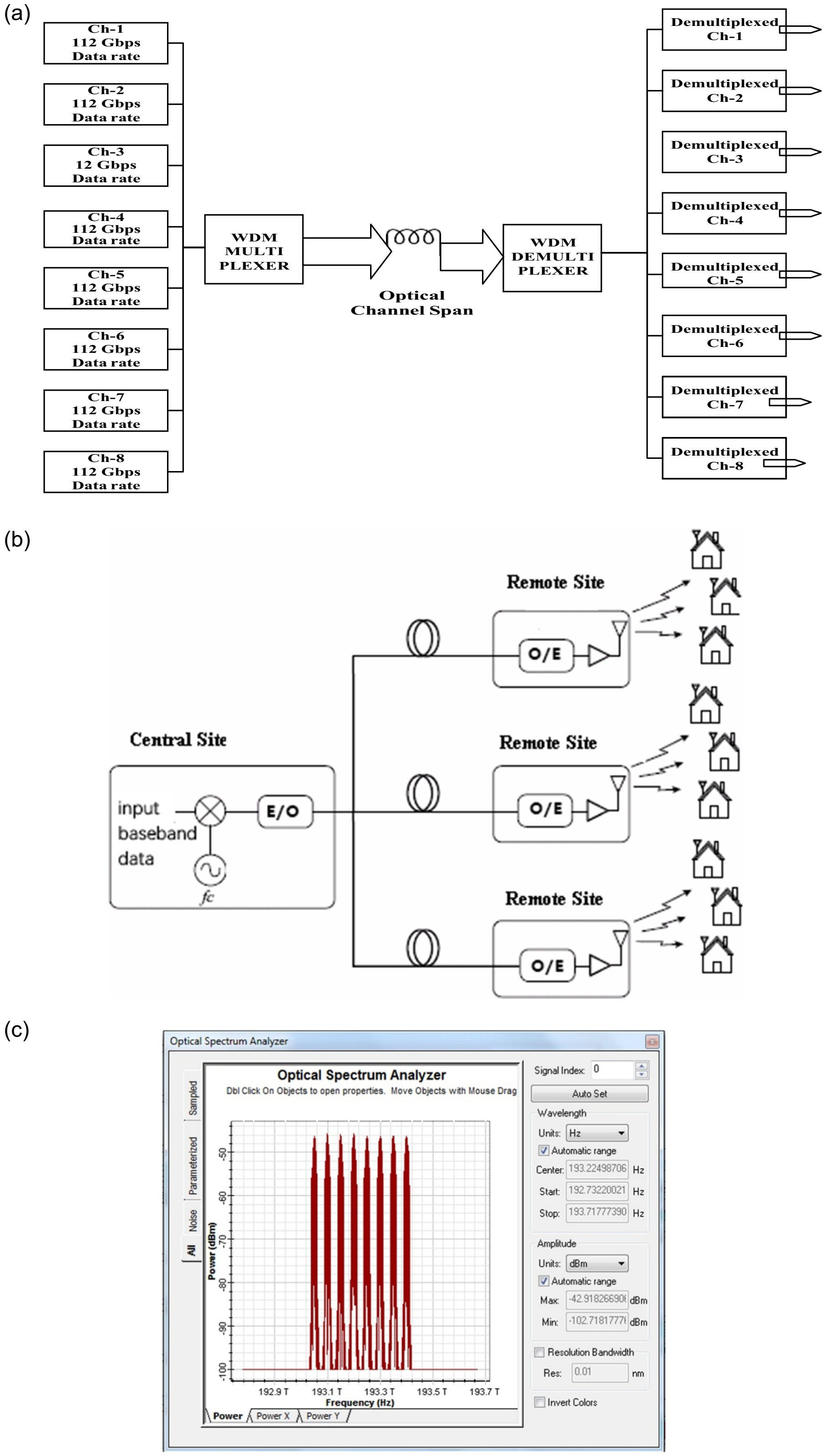
Proposed system offers an 8-channel WDM- ROF system, as illustrated in Figure 1(a). In this system, we employ 8 continuous wave lasers, each operating at a data rate of 112 Gbps, culminating in a remarkable total data rate of 0.896 terabit-per- seconds. These lasers are tuned to optical carrier frequencies ranging from 193.05 THz to 193.40 THz, ensuring efficient channel utilization. We implemented a channel spacing of 50 GHz, a choice made to enhance spectral efficiency. It is worth noting that we have observed a reduction in the Q factor as a consequence of decreased channel spacing [1, 7]. Employed WDM technology serves to raise the cumulative signal power, thereby endowing the system with a remarkably high capacity on the order of Terabits per second all the while maintaining least interference The radio-over-fiber (RoF) system represents a fusion of wired and wireless channels, with information transmitted from central site (CS) to remote site (RS) via optical fiber cables and subsequently relayed from RS to BS through wireless mediums. An RoF system comprises a RS and a CS interconnected through an optical fiber network, as depicted in Figure 1(b). The RoF architecture centralizes radio frequency (RF) signal processing functions, such as frequency up-conversion, carrier modulation, and multiplexing, at the CS. This centralization streamlines the design and maintenance of base stations (BSs), reducing both installation and maintenance costs. By simplifying BS complexity, a single high-capacity CS can manage multiple BSs, effectively addressing issues like cell edge problems and dead zones. The transmitter employs intensity modulation (IM) for the conveyance of RF signals through optical fiber cable. It is essential to utilize external modulators, especially in scenarios involving high frequencies, while direct modulation exhibits simplicity and cost-effectiveness, particularly at lower frequencies [17]. At the destination, users distributed information via wireless manner [18, 19]. Figure 1(b) depicts the typical block schematic of such ROF system. The spectral characteristics of the multiplexed optical carriers are visually depicted in Figure 1(c). Overall, the proposed system is a very promising new development in optical fiber communication technology. It offers the potential to transmit data at very high rates over long distances.

2.2. Channel span section design

We systematically examined various channel span configurations as follows:

1) Configuration with one inline optical preamplifier: In this configuration, we incorporated an optical preamplifier within the channel span and conducted simulations spanning a distance of up to 15,000 km. We utilized standard SSMF optical cable in our test beds. The necessary adjustments to system parameters made as detailed in Tables 1 and 2.
2) Configuration with one optical amplifier outside and one inside the channel span: To explore the potential for improved results, we introduced one optical amplifier outside the channel span and one inside, as depicted in Figure 2. We conducted simulations for this system using the same parametric values as in the previous setup. Our observations revealed a marginal improvement in

Figure 1
(a) Typical block diagram of 8 channels WDM ROF system, (b) Typical block schematic of a ROF system, and (c) Spectrum of 8 WDM ROF channels



Signal Index: 0

Wavelength

Units: Hz

☑ Automatic range

Center: 193.22498706 Hz

Start: 192.73220021 Hz

Stop: 193.71777390 Hz

Amplitude

Units: dBm

☑ Automatic range

Max: -42.91826690 dBm

Min: -102.7181777 dBm

☐ Resolution Bandwidth

Res: 0.01 nm

☐ Invert Colors

Figure 2
With one optical amplifier outside and one inside channel loop span

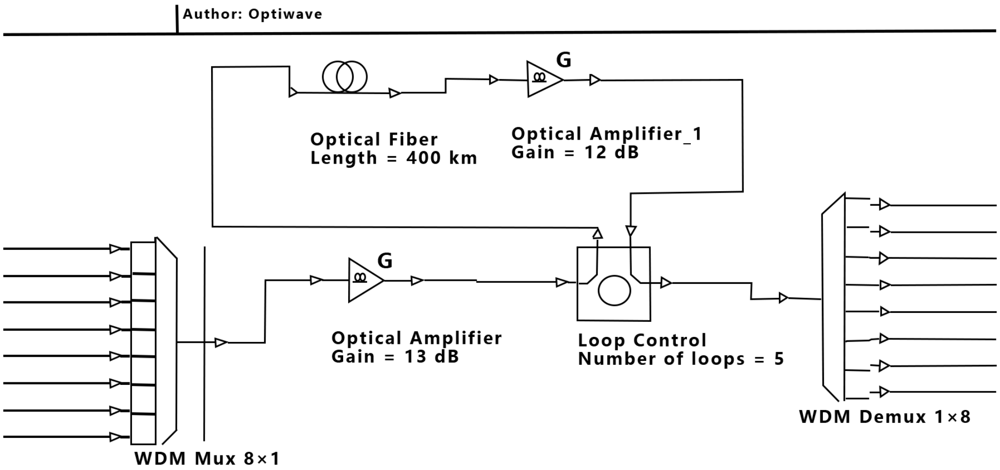


Figure 3
With both optical amplifiers inside channel loop span

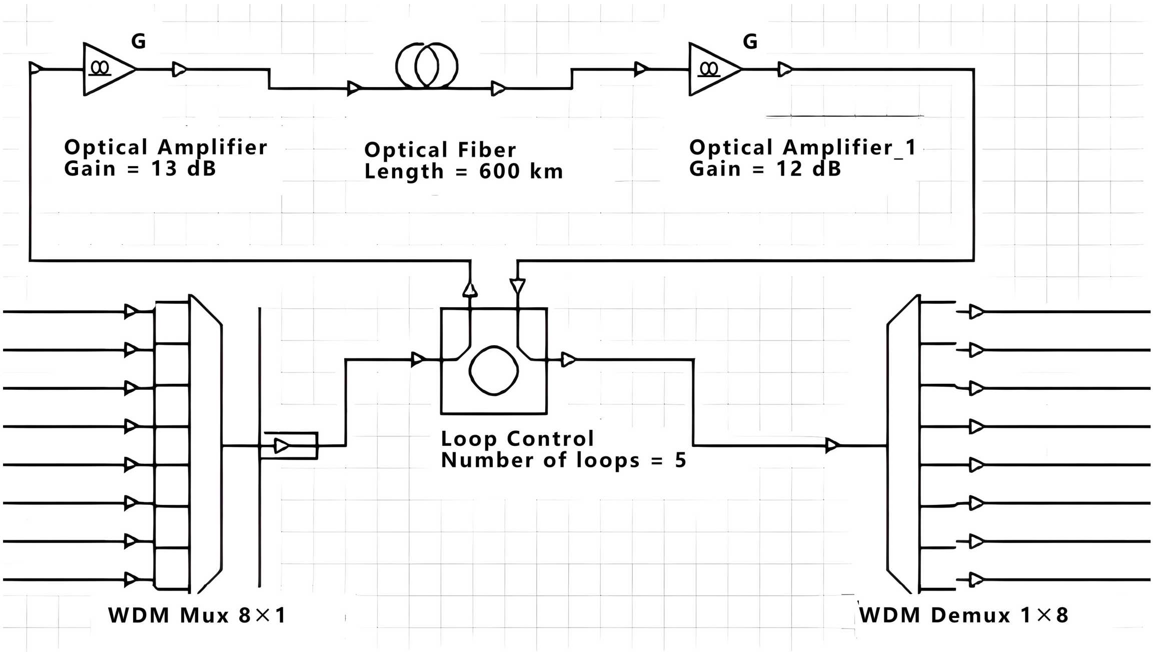


Table 3
(a) Q factor values variation against the different channel spans with different system configurations

DIST.(KM) Vs. Q factor value at	1000	2000	3000	4000	5000	6000	7000	8000	9000	15,000
1000 KM (1st configuration.)	4.463655	4.270521	4.121625	4.259731	4.129177	4.252197	4.129177	4.129177	4.129177	4.129177
2000 KM (2nd configuration.)	4.245705	4.291021	4.291021	4.291021	4.291021	4.291021	4.291021	4.291021	4.291021	4.291021
3000 KM (3rd configuration.)	4.308285	4.232757	4.583419	4.291021	4.291021	4.291021	4.291021	4.291021	4.291021	4.291021

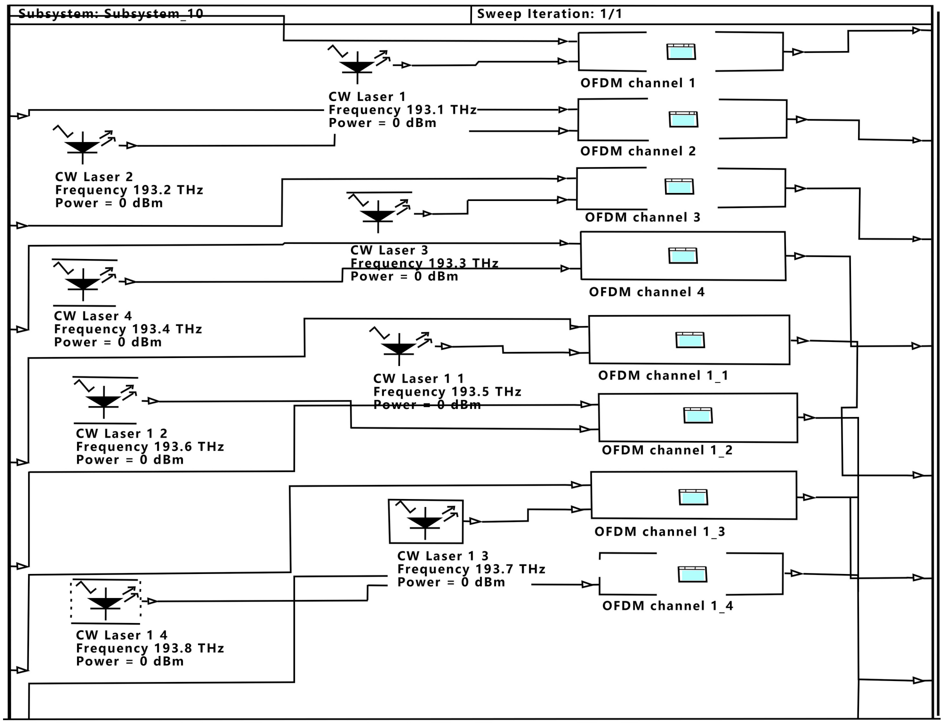
(b) Error vector magnitude factor values variation against the different channel spans with different system configurations

DIST.(KM) Vs. EVM value at	1000	2000	3000	4000	5000	6000	7000	8000	9000	15,000
1000 KM (1st configuration.)	0.46076	0.52391	0.50274	0.52635	0.50086	0.52864	0.50086	0.50086	0.50086	0.50086
2000 KM (2nd configuration.)	0.51747	0.47845	0.47889	0.47889	0.47889	0.47889	0.47889	0.47889	0.47889	0.47889
3000 KM (3rd configuration.)	0.50352	0.48351	0.39542	0.47889	0.47889	0.47889	0.47889	0.47889	0.47889	0.47889

(c) Estimated symbol error rate factor values variation against the different channel spans with different system configurations

DIST.(KM) Vs. ESE value at	1000	2000	3000	4000	5000	6000	7000	8000	9000	15,000
1000 KM (1st configuration.)	1.9E-05	3.3 E-05	3.709 E-05	2.68 E-05	3.61 E-05	2.9 E-05	3.61 E-05	3.612 E-05	3.61 E-05	3.61 E-05
2000 KM (2nd configuration.)	3.5 E-05	2.9 E-05	2.96 E-05	2.96 E-05	2.96 E-05	2.96 E-05	2.96 E-05	2.96 E-05	2.96 E-05	2.96 E-05
3000 KM (3rd configuration.)	3.5 E-05	3.5 E-05	4.508 E-05	2.96 E-05	2.96 E-05	2.96 E-05	2.96 E-05	2.96 E-05	2.96 E-05	2.96 E-05

Figure 4
Inside view of receiver of coherent detection purpose



performance at a distance of 2000 km with this configuration. This improvement can be attributed to the additional optical amplifier compensating for signal loss over the extended channel span. However, it is worth noting that adding more OAs in the optical channel may lead to an optical signal-to-noise ratio penalty. This is due to the active nature of OAs, and the residual nonlinearity of the cable before each successive amplifier contributes to noise, which can degrade system performance.

3) Configuration with both OAs inside the channel span: In our pursuit of achieving improved performance over even longer distances, we introduced two OAs within the channel span and conducted simulations accordingly. The specific configuration employed is depicted in Figure 3.

Remarkably, without the utilization of any specific dispersion compensation techniques, we observed noteworthy improvements in system performance with the setup illustrated in Figure 3. Notably, we achieved optimal results at a transmission distance of 3000 km with this WDM ROF system configuration.

This notable improvement can be attributed to the compensation of optical signal loss within the SSMF by means of the two OAs, both operating in gain control operation mode with respective gain values of 12 dB and 13 dB, as illustrated in Figure 3. To achieve overall channel span, the use of iterative loop is preferable because increased number of loops means an overall same channel span with more number of provided loops offer significant increased Q factor value performance as compared to channel with same span without use of loops. Means more number of iterations of optical signal provide Q^2 valued performance. Here detailed results listed in Table 3(a), (b), and (c) confirm the same.

2.3. Receiver section design

Generally to achieve the optimal performance, a WDM RoF receiver must contain an efficient and speed responding system configuration [4, 20]. Coherent detection significantly enhances receiver sensitivity and optimizes user bandwidth allocation by employing wavelength multiplexing [21].

Figure 4 depicts the utilization of OFDM demodulators for the purpose of coherent detection within our system. Furthermore, Figure 5 provides an illustration of the structure employed for the single-channel QAM-OFDM receiver, drawing from the insights provided in references [3, 20]. As depicted in Figure 1(b), the last stage of the WDM receiver contains radio access points (RAPs). Functioning as a fundamental technology, the RAP serves as an intermediary interface bridging the optical fiber and radio mediums. Its primary role involves the emission of electrical signals seamlessly into the wireless medium. RAP unit includes also an RF amplifier to boost the converted signal to enable further distance coverage [15].

3. Results and Discussion

We conducted thorough and extensive simulations to thoroughly investigate the performance of our proposed 8-channel 112 Gbps (0.896 Tb/s) WDM ROF systems across various scenarios. These simulations executed within the simulation environment provided by Optisystem 13 software. The results derived from these simulations, encompassing the different system configurations, meticulously tabulated in Table 3(a), (b), and (c).

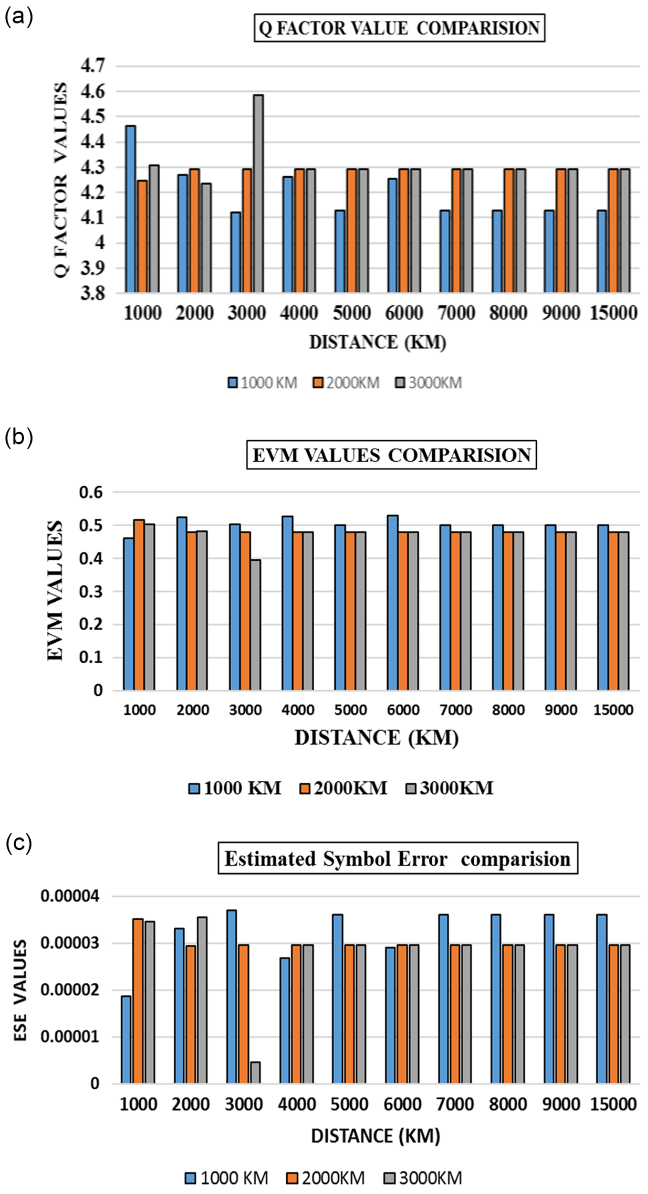
Our research entailed comprehensive simulations to thoroughly analyze the performance of our proposed 8-channel 112 Gbps (0.896 Tb/s) WDM ROF systems under various scenarios. These simulations meticulously carried out using the Optisystem 13 software, providing a controlled environment for our investigations. The outcomes of these simulations, spanning different system configurations, systematically documented and are presented in Table 3(a), (b), and (c) for detailed examination and reference.

In Figure 5(a), (b), and (c), we have plotted the variations of the Q factor, error vector magnitude, and estimated symbol error rate against the channel span. Since different wavelengths in the channels had varying impacts on performance, we computed average values across all eight channels for meaningful comparisons.

At a 1000-kilometer channel span with a single optical amplifier, we observed the highest Q factor at 4.463655, accompanied by the lowest EVM at 0.46076. ESE parameter value 1.9E-05 also observed minimal at this distance. Notably, even better results achieved at 2000 km with the same channel span with configuration shown in Figure 2, resulting in a Q factor of 4.29102122, EVM of 0.4784539, and ESE of 2.94812E-05.

To determine the optimal input power per channel, we investigated power levels ranging from −3 dBm to +3 dBm for a 1000-kilometer channel span. The results revealed that the ideal power level was 0 dBm. This aligns with literature findings, which highlight the influence of amplified spontaneous emission at low power and nonlinearity at high power [7]. Our Q factor results within the −3 dBm to +3 dBm range confirmed this observation. In our proposed system depicted in Figure 3 having both OAs inside channel loop span, we achieved the highest Q factor at 4.58342, with the lowest EVM of 0.39542 and ESE of 4.51E-06 across the entire channel span.

Figure 5
(a) Q factor values variation against the different channel spans, (b) Error vector magnitude factor values variation against the different channel spans, and (c) Estimated symbol error rate factor values variation against the different channel spans



As we varied the transmission distance from 1000 to 15,000 km, we noted that performance judging parameter values deviated from their expected ranges, except at 3000 km. This highlights the dominant impact of fiber impairments categorized as linear and nonlinear at different distances. The increased EVM and ESE values at other distances indicated higher signal corruption, underscoring the suitability of 3000 km as the optimal channel distance for our proposed WDM ROF system. To further enhance performance, DSP can be implemented at the receiver end [7].

4. Conclusion

We claim an innovative design: an 8-channel 112 Gbps (0.896 terabit-per-seconds) 32 QAM-OFDM WDM RoF link system. Our analysis covered various suggested configurations such as an optical preamplifier within the link, one optical amplifier outside channel loop span, and one inside loop span, and both amplifiers in the channel span incorporated channel spans from 1000 to 15000 Kms with recirculating loops concept. Our comprehensive simulation results conclusively established that the most optimal system performance attained with a channel span of 3000 Km with assessing suggested diverse system configuration.

In view of these findings, we confidently assert that projected 8-channel 112 Gbps WDM ROF using 32QAM-OFDM system exhibits outstanding performance when operated at a power level of 0 dBm and a transmission distance of 3000 km. This transmission distance is notably appealing for upcoming next-generation systems engineered for catering long-reach applications. To enhance system performance further, we recommend exploring the potential of distributed amplification via Raman amplifiers in such system configuration [15].

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

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