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Research Article

Transmission Performance Analysis of WDM Radio over Fiber Technology for Next Generation Long-Haul Optical Networks

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This paper presents a detailed study of N-channels Wavelength Division Multiplexing (WDM) Optical transmission system using Radio over Fiber (RoF) technology. The study was applied to optical long-haul networks to overcome the nonlinearity effects, chromatic dispersion, and signal loss. For this purpose, Fiber Bragg Grating (FBG) has been implemented in 4-channels, 8-channels, and 16 channels WDM transmission system network at 10 Gb/s to compensate the dispersion and the nonlinear distortion. The use of erbium-doped fiber amplifiers (EDFA) has been also investigated to improve the quality of the transmission system. In Digital RoF, the impact analysis of modulation types such as Differential Phase-Shift Keying (DPSK) and Quadrature Amplitude Modulation (QAM) is also introduced. Constellation diagrams, received optical power, types of modulation, fiber dispersion, channel spacing variation, and laser power were considered to validate the study with the existing studies. All results achieve good reliability performance and prove the efficiency of the presented model.

1. Introduction

In the near future, the world's population is expected to live in smart cities as new urban environments that are capable of managing the information and the communication technology in new network infrastructures. These new platforms are intended to enable economic, social, and environmental well-being for their citizens in services such as administration, education, health care, public safety, real estate, transportation, and utilities [1]. Incorporating of optical networks might be the answer to the expected extensive needs of new telecommunication systems, as they could supply the bandwidth needed for end users. Accordingly, numerous researcher have analyzed the smart cities requirements in order to propose a hybrid optical-wireless network architecture acting as the Metro Access network, mainly focusing on the network design and planning [2, 3]. The optical systems of the new generation have developed and installed new techniques such as Wavelength Division Multiplexing (WDM) to meet the smart cities challenges and the increasing data traffic at higher rates [4, 5]. WDM is a multiplexing technique for new fiber optic systems that multiplex a number of optical bearer signals on a single optical fiber by disposal various wavelengths to carry various signals. This technique allows a multiplication in capacity and it is possible to achieve bidirectional transmission over one strand of fiber optic. Radio over Fiber (RoF) is also one of the latest technologies in optical communication systems that provide effective convergence of optical and wireless access network system [6]. RoF is a technology whereby light is modulated by a radio signal and transmitted over an optical fiber link to facilities wireless access [7]. The use of RoF in the area of smart cities is very modern but its application has not yet been implemented for large scale [8]. Digital RoF was performed in numerous applications such as mobile access network, remote antenna in satellite communication, or wireless access systems [9, 10]. Different studies have been conducted recently in relation to Radio over Fiber (RoF) and Wavelength Division Multiplexing (WDM) networking aiming for a hybrid communication system that can improve the efficiency on big speed and small cost accessing networks [11, 12]. However, there are still many problems in which researchers are still looking for better solutions, such as chromatic dispersion, signal losses, and nonlinear effects, which have a significant impact on the performance of optical communication networks. There are two classes of nonlinear impacts. The first is due to the interaction between light waves with phonons. The second arises from the dependence to the refractive index on the intensity of applied electric field [13–15]. In a WDM system, these effects place constraints on the spacing between adjacent wavelength channels, cap the maximal power on all channels, and may as well limit the maximum bit rate. In this paper, we attempt to develop a new WDM transmission model of N-channels based on RoF technology that is suitable for use in future transmission systems operating in C-band coverage. For this purpose, we propose to use the uniform Fiber Bragg Grating (FBG) in 4-channel, 8-channel, and 16 channel WDM transmission system at 10 Gb/s to compensate the dispersion and the nonlinear distortion in the optical communication system [2, 14, 16]. The use of erbium-doped fiber amplifiers (EDFA) in the developed optical communication network has been investigated to improve the quality of the transmission system [17]. The impact analysis of modulation formats in Digital RoF such as Differential Phase-Shift Keying (DPSK) and Quadrature Amplitude Modulation (QAM) is also introduced. The developed model has been compared with a previous work in literature that uses RoF technology based on constellation diagrams, received optical power, types of modulation, fiber dispersion, channel spacing variation, and laser power. The results achieve always a good reliability performance, which proves the efficiency of the proposed model.

2. Digital Radio over Fiber in WDM Technology

In this work, two main parameters are considered to analyze the performance of the optical transmission system, which are the nonlinearity at the fiber link and the input power of the laser source. The model was setup in two parts: the transmitter and the receiver. RoF link consists of the direct modulation technique in which we use directly modulated laser at ~1550 nm wavelength with ~0 to 25 dBm power and 25 MHz line width. The pseudorandom bit sequence generator (PRBS) generate baseband signal which is used with 10 Gbps to modulate a high frequency RF. The last is the frequency carrier that uses electrical modulation which will shift this spectrum of data signal to frequency. Differential Phase-Shift Keying (DPSK) is proposed for this electrical modulation, which is a noncoherent version of PSK; it eliminates the need for a coherent reference signal at the receiver. Two amplifiers of 45 dB and 31 dB gains are used within a signal mode fiber of 100 km length with 0.2 dB/km attenuation. At the receiving side PIN photodiode uses an optical detector with responsivity of 1A/W & Dark Current of 1nA. The input signal is m-QAM and m-DPSK signal; the Directly Modulated Laser Measured Wavelength is from 1550 nm until 1553 nm. The QAM and DPSK transmitter signals are generated by M-array pulse generator, QAM and DPSK modulators, and QAM and DPSK sequence generators. The QAM and DPSK modulated signal will be transmitted through radio over fiber. The QAM and DPSK demodulator are used for detection. Simulation results are analyzed using oscilloscope visualizer, electrical cancellation, optical power meter, and electrical power meter.

Figure 1 shows the schematic block of RoF system using DPSK and QAM modulation techniques considered in the study using the advanced tools of Optisystem 7.0.

3. Results and Discussions

In order to develop the new model based on the WDM technology for RoF systems implemented in this paper, firstly, we proposed the analysis detail of the nonlinear distortion with electrical cancellation point results. Next, we compare the effect of the different types of amplifiers on the system output power. With the aim of compensating the dispersion phenomena, we integrate the Fiber Bragg Grating and then we study the order of the modulation effect to resolve the nonlinear distortion. Afterward, we discuss the signal source effect on the output power to determine the convenient input power. Finally, we investigate the behavior of the channel spacing and fiber optic dispersion on the output power.

Constellation diagram can be useful to compare the transmission performance and visualize the interferences and the distortions of digitally modulated signal. Figure 2 illustrates the constellation diagrams of the transmitted signals for the main modulation format investigated in this paper: Differential Phase-Shift Keying (16 DPSK, 32 DPSK, and 64 DPSK) where all symbols lie on one circle and have the same optical power in the ideal case, as well as the shaped Quadrature Amplitude Modulation (16 QAM, 32 QAM, and 64 QAM). The modulated input signal transmitted through RoF is set at 1 GHz with amplitude of ~ 7 a.u. (arbitrary unit) for QAM and ~ 1 a.u. for DPSK. The received signal has amplitude of ~0.9 a.u. for QAM and the same value for DPSK.

It can be observed from Figure 2 that the distribution of DPSK modulation technique is better than QAM modulation, which proves that QAM decrease relatively the system efficiency compared with DPSK. The amplitude reduction of both modulation techniques at the receiver is due to the nonlinear distortion in RoF systems.

In order to transfer signals over long haul, the compensation of signal attenuation is highly needed within the fiber. For this reason, different types of optical amplifiers have been developed and implemented, such as Semiconductor Optical Amplifier (SOA), Raman amplifier, and EDFA. Table 1 shows the effect of the different types of amplifiers on the output power when the length of fiber is set at 100 Km.

It can be noticed from Table 1 that EDFA provide a better result for output power which varied for 2-optical channels compared without an amplifier, with EDFA, and with SOA and Raman Amplifier for all output power values.

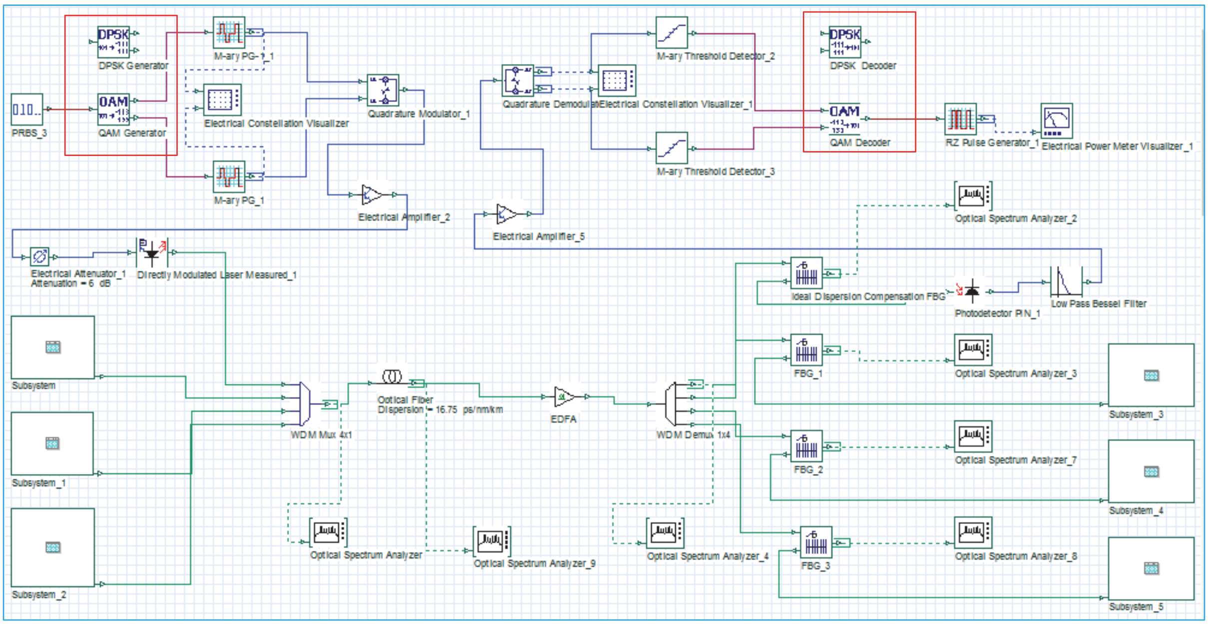

Figure 1: WDM RoF system using QAM modulation technique with 4-optical channels.

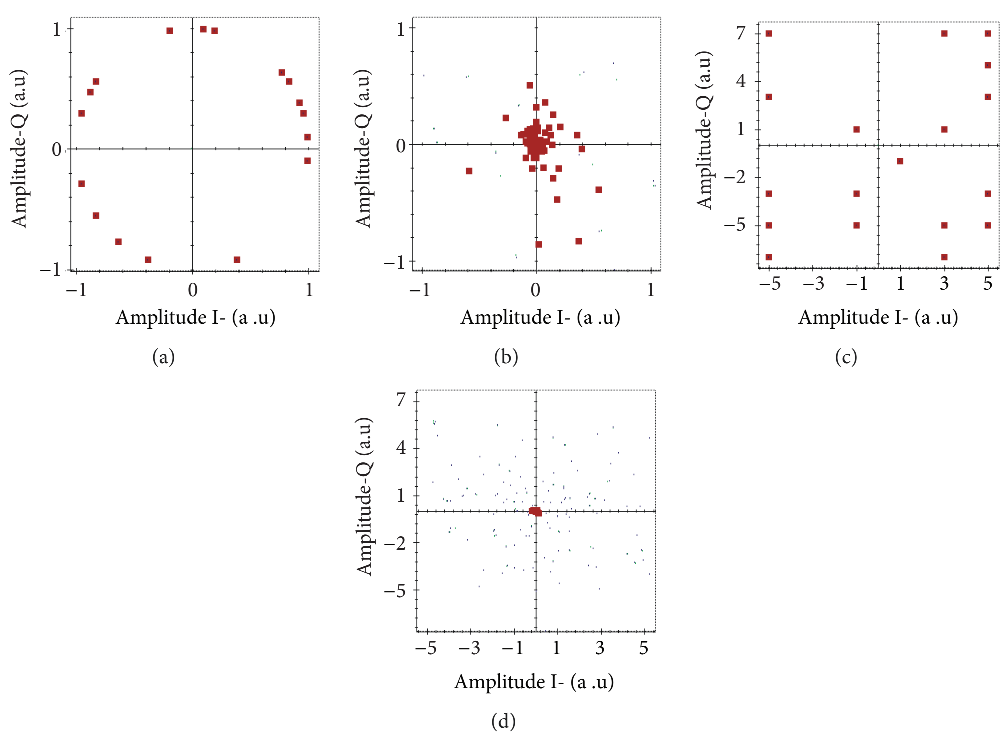

Figure 2: Cancellation of the transmitted signal: (a) using DPSK and (c) using QAM and received signal: (b) using DPSK and (d) using QAM.

Table 1: Effect of types of amplifiers on output power.

Types of amplifier	Without amplifier	EDFA	SOA	Raman
Output Power for Channel 1 (dBm)	23.95	23.98	23.96	-100
Output Power for Channel 2 (dBm)	24.22	24.24	24.07	-100

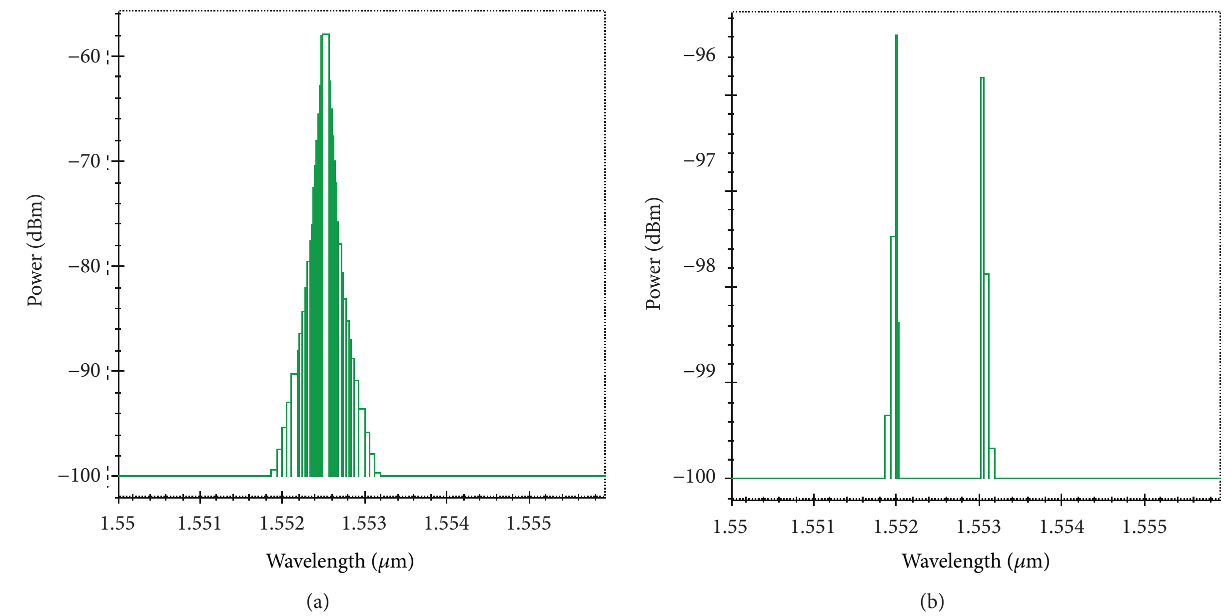

FIGURE 3: Nonlinear effects at the received spectrum of the 2^{nd} channel, (a) without FBG and (b) with FBG.

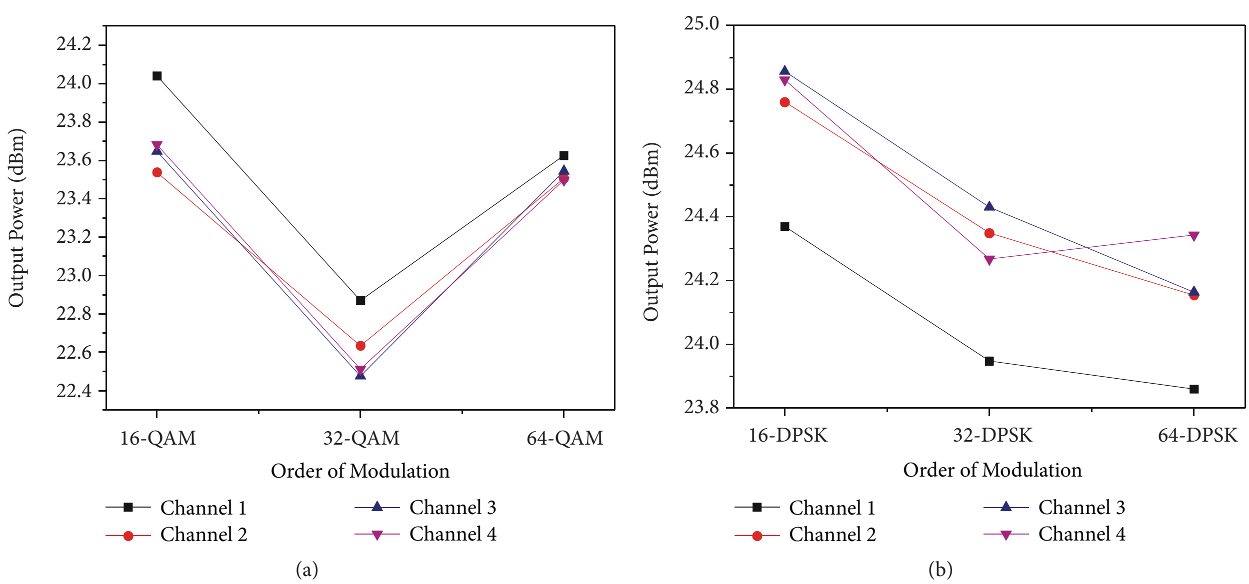

FIGURE 4: Effect of (a) QAM and (b) DPSK modulation order on output power.

In the interest of improving the transmission quality and reduce the nonlinear distortion of our model, we propose to use Fibers Bragg Grating (FBG) which can boost the system performance. The latter has negligible nonlinearity, low insertion loss, better coverage, and high resistance to Radio Frequency Interferences, either when used for routing wavelength in WDM systems or when used as a dispersion compensator for a long distance fiber network. The introduction of this device in the proposed WDM transmission system can help to eliminate the additional pulses generated by the nonlinear effect as shown in Figure 3.

In order to analyze the reliability and trend for high-order optical modulation signals, DPSK and QAM modulation formats are investigated based on the output power in Figure 4.

It can be observed from Figure 4 that, by increasing the order of modulation (i.e., QAM to 64 QAM and DPSK to 64 DPSK), the effect of nonlinear distortion can be reduced. Table 2 illustrates the performance comparison of the developed model with a previous work proposed by other authors [12] based on the output power in high-order modulation.

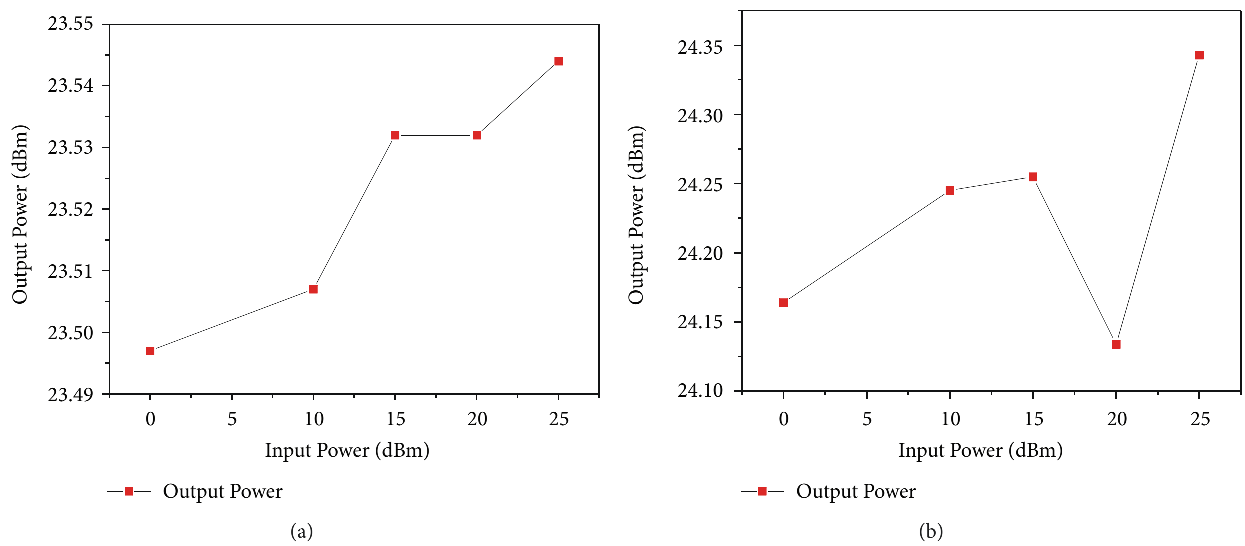

Figure 5: Effect of laser power on output power using (a) QAM and (b) DPSK modulation techniques.

Table 2: Comparison order modulation for previous model and developed model.

Order of Modulation	Output Power for [12] (dBm)	Output Power for our model with QAM (dBm)	Output Power for our model with DPSK (dBm)
16	-31.719	24,040	24,829
32	-31.736	22,869	24,267
64	-31.932	23,625	24,343

Table 3: Comparison level power of the conventional and proposed models.

Laser Power (dBm)	Output Power for [18] (dBm)	Output Power for Proposed Model with QAM (dBm)	Output Power for Proposed Model with DPSK (dBm)
0	-31.932	23,497	24,164
10	-11.933	23,507	24,245
15	-1.933	23,532	24,255
20	8.067	23,532	24,134
25	18.067	23,544	24,343

It is clearly observed from Table 2 that our model provides better output power regardless of the order of modulation, either 16, 32, or 64, which demonstrate its efficiency.

The optical power produced by a laser diode is linearly proportional to the input electric current of driving. Besides, the move to deploy broadband (>=10 Gbps optical channel) in the system cannot be done without taking into account nonlinear effects and reduce their impact on these systems. This is why nonlinear effects are now the most important dominant of the performance of communication systems based on optical fiber for long distances broadband.

As shown in Figure 5, the output power of received signal is increased by increasing the laser power in both cases of modulation technique (QAM and DPSK).

Table 3 shows sample comparisons made between our proposed model and the model proposed by other authors [18] using the same initial setting in input power.

The dispersion is widening a pulse width as it travels through a fiber. As a pulse wider can be expanded sufficiently to interfere with adjacent pulses (bits) on the fiber, resulting in intersymbol interference, the dispersion limit of the bit spacing, and the maximum transmission rate on an optical fiber channel. Another form of dispersion is the dispersion of a material or a chromatic dispersion. A third type of dispersion is the dispersion guide. In our case, we analyzed the channel dispersion. Figure 6 shows the fiber dispersion variation from 1ps/nm/km to 16.75ps/nm/km.

It can be observed from Figure 6 that the sideband power is -58 dBm in QAM modulation, whereas the side band power is -56.9 dBm in the DPSK modulation. When the fiber dispersion is set to 16.75ps/nm/km, the power level of the new interfering wavelengths generated decreases to -58.6 dBm for QAM and -57.9 dBm for DPSK. Therefore, when the dispersion parameter increases, the power level decreases, which reduces the nonlinearity effect.

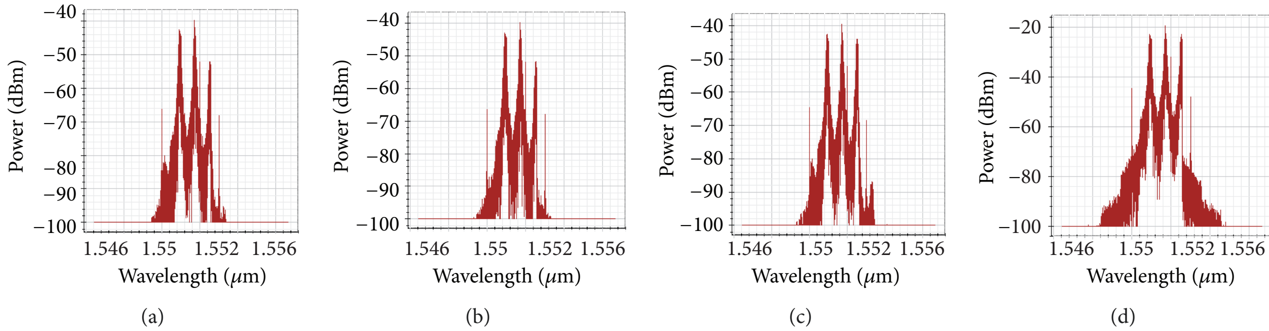

Figure 6: Optical spectrum at the output of the fiber when dispersion of fiber is set at (a) 1 PS/nm/km and (b) 16.75 PS/nm/km using QAM modulation technique and (c) 1 PS/nm/km and (d) 16.75 PS/nm/km using DPSK modulation technique.

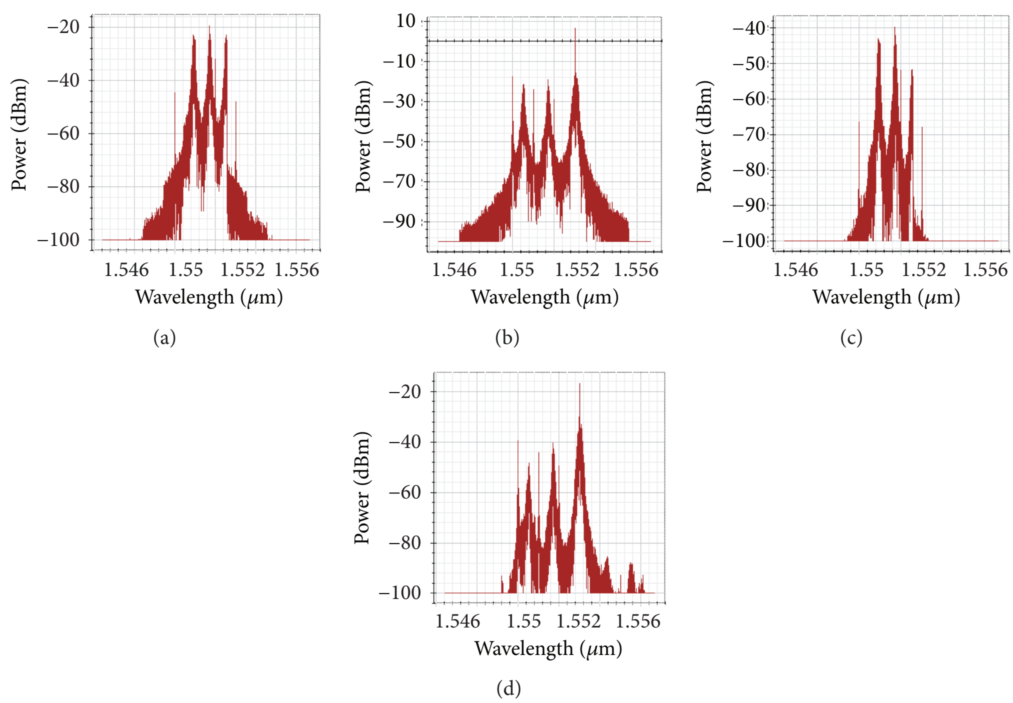

Figure 7: Optical spectrum at the output of fiber when the channel spacing is set at (a) 0.1 nm and (b) 1 nm using DPSK modulation technique and (c) 0.1 nm and (d) 1 nm using QAM modulation technique.

This section is to deal with some nonlinearity effect generated by FWM in the WDM system. In this case, the factors that influence the quality of the transmission signal are the impact of original wavelength, the generated cross products, fiber characteristics, and channel spacing. The latter can be defined as the minimum frequency separation between two multiplexed signals. For this reason, we implement three values of channel spacing that are 0.1 nm, 0.5 nm, and 1 nm for both modulation techniques. The interfering wavelengths generated are 1551 nm and 1552.9 nm as shown in Figure 7.

Table 4 shows the output with each side band of power. When the channel spacing is 0.1, nm, 0.5 nm, or 1 nm the side band power increases and hence the nonlinearity effect is decreased. Hence, the sideband power falls with the increase in channel spacing and accordingly the effect of the FWM is decreased.

4. DPSK and QAM Output Power Comparison

To be able to identify the performance tendencies for both modulation (QAM and DPSK), the output power is investigated by conducting comprehensive calculations based on laser power. Figure 8 shows two modulation formats the DPSK and QAM output power variation.

It can be observed from Figure 8 that the output power is significantly enhanced in DPSK modulation format compared to QAM modulation. It can also be noticed that DPSK shows clear advantages over QAM regarding the power level and nonlinear distortion. This article clearly supports article

Table 4: Channel spacing variation.

Channel Spacing Variation (nm)	Power of QAM Modulation (dBm)	Power of DPSK Modulation (dBm)
0.1	-20	-19
0.5	-18.2	-18
1	10	10.4

Table 5: N-optical channels WDM system for RoF.

Laser Power (dBm)	Output Power for 4-Channels (dBm)	Output Power for 8-Channels (dBm)	Output Power for 16-Channels (dBm)
20	24,134	23,860	23,860
25	24,343	23,881	23,881

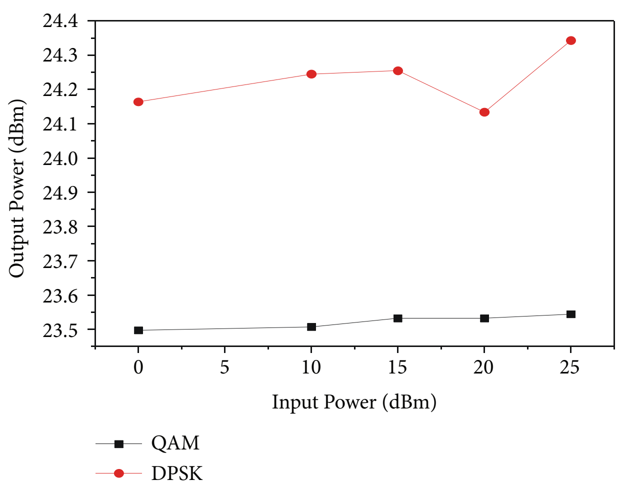

Figure 8: Performance of QAM and DPSK modulation technique.

[16] that DPSK is better modulation technique than QAM for RoF system because of its highest performance in output power.

5. N-Optical Channels WDM System for RoF

As an example for N-Optical channel WDM transmission system, we studied the following cases: 4-channel, 8-channel, and 16-channel RoF WDM transmission system operating around 1550 nm with channel spacing of 1 GHz. The previous analysis is applied again on these multiplexed structures to evaluate their performance and validate the reliability of our model. Table 5 shows the output power of the 1st channel versus the laser power in 4-channel, 8-channel, and 16 channel WDM systems.

It can be observed from Table 5 that the proposed system keeps its advantages even when channel number increases. For this reason, we compared our model with the architecture proposed in [11], who treated only some properties of non-linearity problems effect in WDM Radio over Fiber System, besides the four-wave mixing effect (FWM) that is one of the most influential factors in the wavelength division multiplexed for Radio over Fiber (WDM RoF). Thus, two signals with wavelength 1550 nm and 1551 nm are transmitted. The transmitter consists of continuous wave (CW) laser having 0 dBm power level and the output modulation of 2.4GHz delivered by a sine generator wish transmits modulated radio signal. The two signals are then combined using WDM multiplexer and launched through the optical fiber with distance of 25 km. Figure 9 shows our model implemented in the architecture proposed by [11].

Table 6 shows the comparison results in terms of fiber dispersion between our model and the model proposed by [11].

It can be seen from Table 6 that our model provides better output power and low dispersion level. So we can conclude that the proposed transmission system presents a very satisfactory performance for Radio over Fiber Technology based on WDM system in optical long-haul networks.

6. Conclusion

In this paper, N-channels WDM Optical transmission system using Radio over Fiber (RoF) technology was studied. The nonlinearity effects, the chromatic dispersion, and the signal loss for each channel using FBG and EDFA have been corrected in order to enhance the optical long-haul network performances. The most convenient design parameters are optimized and used in the new WDM RoF system. For this purpose, we analyzed the network performance of N-channels for WDM with QAM and DPSK modulation techniques to study the nonlinearity effect. In addition, two different modulation techniques (DPSK and QAM) were compared and presented. Consequently, the WDM RoF system with DPSK offers good enhancement in comparison with QAM technique. Useful results show that, by integrating the FBG, EDFA, and DPSK modulation technique, the non-linearity effects, the signal loss, and the chromatic dispersion have been resolved, respectively. Results with previous works have been compared in terms of the output power proving performed parameters.

Data Availability

The technical data used to support the findings of this study may be released upon application to the SMART TECH

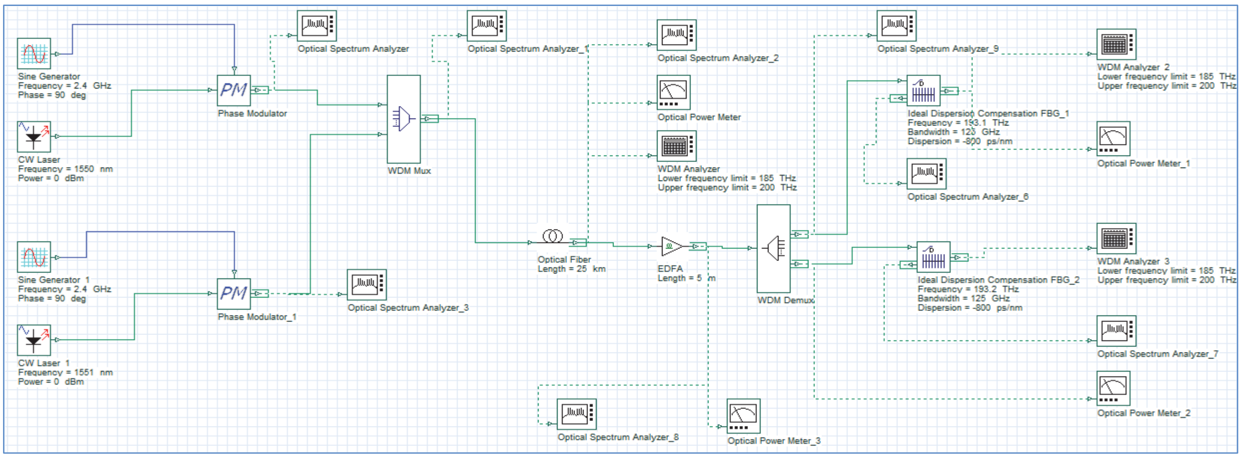

FIGURE 9: Simulation the previous model whit our proposed parameters.

TABLE 6: Effect of variation in dispersion of the fiber optic for conventional and proposed models.

Dispersion of fiber (PS/nm/km)	Output Power for [11] (dBm)	Output Power for Proposed Model (dBm)
1	-71	-46.06
16.75	-63	-45.87

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

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