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Performance Analysis of Modulation Formats for Next Generation RoF Systems

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ABSTRACT Radio over fiber (RoF) has found to be one of the most effective communication techniques. It has the tendency to incorporate both optical fiber and free space radio paths. In this research article, importance, benefits, and applications of RoF system are discussed in detail for futuristic networks. The performance of RoF system is visualized by modulating the data with the RF signal having same frequency at both transmitter and receiver ends. Initially, the performance is checked using non-return to zero (NRZ) format and later compared with duobinary (DB) and carrier suppressed return to zero (CSRZ). Various simulations are performed which directly affect the system performance. Important parameters such as RoF link distance, data rate, transmitter power, amplifier gain, and RF signal frequency are tested. The operation is carried out at 1550 nm wavelength and 30 GHz RF frequency. System is optimized to receive the transmitted waveforms successfully. Simulations are performed in Optisystem 17.0 and MATLAB. For the analysis, the results are plotted using Q-factor and BER values.

INDEX TERMS Radio over fiber, modulation formats, optical fiber network (OFN), radio frequency, BER, Q-factor, fiber length.

I. INTRODUCTION

Over the past few decades, there has been tremendous increase in the number of subscribers and demand for high-speed data transmission across the world. Large coverage, online-connectivity and high mobility have become pervasive requirements for the current communication systems. The demand of efficient systems which support high data rates are the future of next generation networks. While optical fiber provides huge bandwidth and supports long distance communication, the radio wave frequencies compensate the spectrum congestion and provide large bandwidth in wireless domain [1]. RoF is a technique that offers access to the channel bandwidth. Thus, it is used to regulate the network traffic in case of wireless networks [2]. RoF link possess the important characteristics of both optical fiber link and free space radio [3]. This fiber based wireless access helps meeting the demands of real-time high-capacity multimedia services [4]. Further, optical signal generation based on RoF technology has many applications in practical life for high frequency wireless systems [5].

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A. WHAT ARE RoF SYSTEMS? HOW DO THEY WORK?

RoF systems can be divided into three main subsystems which include a central station as transmitter, optical fiber network and a base station as receiver, shown in Fig. 1. Each subsystem performs different functions. The signal generation and modulation techniques are controlled at central station (CS) whereas, base station (BS) detects the signal which comes from the optical fiber network (OFN). CS transmitter mainly comprises of data source and laser whereas BS receiver consists of photodiode. The electrical signal converts into optical signal in the CS and it uses OFN to communicate with the BSs. OFN utilizes its remote nodes from where the optical signal gets amplified and distributed to BSs using

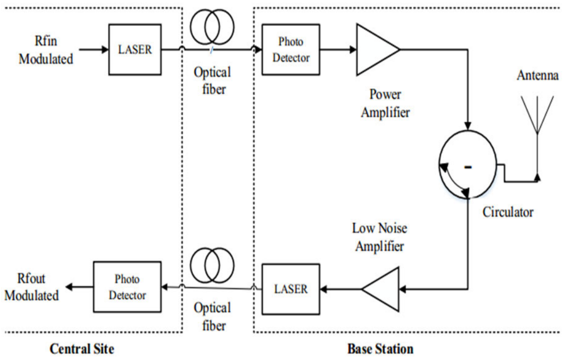

FIGURE 1. A typical RoF system.

demultiplexing technique. The BS consists of small antenna unit known as remote antenna, which converts the optical signal back to electrical domain and give it to the end user. Similarly, the BS receives the radio signals from the end users, converts them into the optical domain and transmits the information to CS via OFN [1]. Thus, RoF system provides a single shared location for centralize RF signal processing [2].

The main requirement for RoF link includes duplex operation i.e., uplink and downlink, reasonable link length and high-performance optical components [3]. Usually, RoF system makes use of two types of modulation i.e., direct and external modulation. In direct modulation format, the RF signal varies directly with the bias current of semiconductor laser diode. Whereas the external modulators integrate with either electro-absorption or Mach-Zehnder interferometers [4].

B. ADVANTAGES OF RoF SYSTEM

RoF systems have several advantages over the coaxial cable and wireless systems. The major benefits are low attenuation loss due to optical fiber and large bandwidth around THz frequency range as compared to the wireless frequency. The information signal travels in the form of light so there are less chances of radio frequency interference. Although its installation requires huge cost, but its maintenance is less costly and reduces the consumption of power compared to wireless systems [1]. RoF system provides operational flexibility. In case of micro-wave generation, the system generates signal irrespective of the format [2]. These systems have enhanced cellular coverage [3]. In contrast, the conventional devices require a lot of circuitries. Thus, RoF technology has the great potential to replace the existing complex systems.

C. DISADVANTAGES OF RoF SYSTEM

RoF systems require high-speed optical components and complex radio wave generation techniques. The chromatic dispersion affects the signal even over a smaller distance which requires implementation of advance modulation formats and transmission schemes. Thus, we need to develop the optical components operating on radio wave band and better techniques for the efficient transmission of radio signals over the optical fiber. RoF transmission system is analog in nature. So, signal distortion and noise-like signal disturbances should be considered as important factors [2].

D. LITERATURE REVIEW

An overview of RoF system illustrating signal generation, comparison of different modulation schemes and fiber characteristics along with the receiver and detection mechanism is described in [1]. The comparison of orthogonal frequency division multiplexing (OFDM) modulation with quadrature amplitude modulation (QAM) shows that OFDM works better as modulation format than QAM. An evaluation of RoF technology based upon different coding formats is given in [2]. A RoF system is analyzed for NRZ encoding in [3] and it is concluded that due to high peak power, NRZ suffers more from non-linearities. Studies show that we can operate better using RZ modulation in high power regime compared to NRZ [4]. A 20 Gb/s W-band wireless transmission has been demonstrated using optical signal generation in [5]. The Quadrature phase shift keying (QPSK) signal is optically synthesized and direct optical up-conversion helps for the generation of W-band RoF signal in both wired and wireless transmission. Similarly, in [6] authors show 40 Gb/s W-band RoF signal generation using W-band electrical receiver. The coherent optical/wireless network provides capacity greater than 40 Gb/s and thus, making signal useful for dual mode operation. A simplified RoF model is proposed in [7] using QAM transmitter. Although modulation format is complex, but it provides the transmission rate six times more than the signaling rate.

The idea of generating OFDM symbols using QAM is described in [8]. The OFDM-RoF systems with external intensity modulation are found to perform better. The combination of OFDM and RoF is useful for both short and long-haul communication with high data rates. A comparison of different intensity modulation techniques is given in [9] for FSO based RoF-WDM system. Using DWDM environment multiple wavelengths are transmitted to increase the data rates. In [10], authors used the OFDM modulation format but the performance of their RoF system is limited mainly due to the dispersions. However, they implemented DSP-based cancellation techniques at the receiver end to improve the quality of signal.

A summarized literature review including some other papers on RoF is shown in Table 1.

Applications of modulation schemes used in our paper along with RoF include: a high performance based duobinary receiver based on self-mixing for millimeter-wave radio-over-fiber systems [21]. NRZ and RZ based RoF communication system can be found in 5G applications [22]. Similarly, a wide band long distance RoF communication system based on CSRZ format can be seen in [23].

E. CONTRIBUTIONS

Major contributions of this paper can be summarized as,

1) Different modulation formats like CSRZ, NRZ and Duobinary are compared to check their performances

TABLE 1. Literature review.

Ref	Objective	Modulation formats	Q-factor	BER	Applications
[1]	Performance analysis & optimization of RoF link	QAM-OFDM	√	√	Outdoor
[2]	Study of RoF with different channel coding schemes	NRZ, DRZ, and MDRZ			Outdoor
[3]	Performance analysis of RoF system	NRZ	√	√	
[4]	Simulation of RoF system & its analysis	NRZ	√	√	
[5]	20-Gb/s QPSK W-band wireless link using RoF	QPSK		√	Outdoor
[6]	40-Gb/s W-band 16-QAM RoF generation & transmission	16-QAM		√	
[7]	Performance analysis of RoF Indoor system	64-QAM		√	Indoor systems
[8]	Coherent optical OFDM-RoF employing 16QAM external modulation	16-QAM	√	√	NGN
[9]	FSO based RoF WDM system analysis	AMI, CSRZ etc.	√	√	WDM
[10]	RoF-based Optical Fronthaul Technology	OFDM			5G
[11]	OFDM signal Improvement in RoF system	OFDM			
[12]	High speed wireless system for WLAN	AMI	√	√	WLAN
[13]	Performance analysis of coded OFDM signal for RoF system	COFDM, QAM, QPSK	√	√	
[14]	Simulation of Full-duplex RoF system	BPSK	√	√	Full-duplex RoF
[15]	Comparison of RoF system with different modulation formats	DPSK, OQPSK, MSK, CPFSK	√	√	NGN
[16]	RoF system analysis for HAN using different line coding schemes	NRZ, RZ, Gaussian line coding	√	√	
[17]	Analysis of OFDM scheme for RoF system	QAM-OFDM			Outdoor
[18]	Comparison of RoF system using different digital modulation schemes	DPSK, OQPSK, MSK, CPFSK	√	√	Outdoor
[19]	Performance Analysis of Full-Duplex NG-PON2-RoF System	QAM	√	√	NGN
[20]	High data rate digital RoF system	QAM	√	√	5G

in RoF environment. The three schemes have been selected as these are not worked out before this particularly in their comparison of working with RoF. Further, all the three current chosen schemes are intensity-based modulation schemes which are different from QAM & QPSK as phases are not involved in these schemes.

2) A detailed network analysis is performed while considering following parameters,
   - Fiber length
   - Data rate
   - Tx power
   - Amplifier Gain
   - RF frequency
3) System parameters are optimized to get good Q-factors and low BER.

The rest of the paper is organized as follows. Section-II comprises mathematical modeling and elaborates design parameters required for the RoF system. System design is presented in section-III followed by results and discussions in section-IV. Finally, the paper is concluded in section-V.

II. MATHEMATICAL MODEL

Neglecting laser non-linearities, the instantaneous optical power output P(t) from the laser in response to input electrical signal s(t) is given by [24],

$$p(t) = [1 + ms(t)]P_o \tag{1}$$

where P is the optical power and m is modulation index. The information RoF signal from Mach-Zehnder modulator output is described by the following expression,

$$E(t) = \sqrt{Po}.\cos[\frac{\pi}{2V_\pi}.(-V_o - V_N(t) + 2V(t) + \Delta V_1)] \tag{2}$$

The current produced at photodetector can be calculated by the following equation,

$$I_D(t) = \rho P(t) \tag{3}$$

where, ρ is the detector responsivity.

The total loss due to the ROF link with resistive matching at the O/E and E/O converter is given by the following equation,

$$L_{op} = 20\log\left(\frac{G_m R}{0.001}\right) + 10\log\left(\frac{Z_{out}}{Z_{in}}\right) + 2OL \tag{4}$$

where, Gm is the modulation gain of the laser. Z_{in} and Z_{out} are the input and output impedance of the laser transmitter and receiver, respectively. OL defines the optical losses including fiber and connector losses and can be further defined as,

$$OL = 2L_c + \alpha L_F \tag{5}$$

where, α is the fiber attenuation, Lc is the connector loss and LF is the length of the fiber link.

The optical signal to noise ratio can be defined as,

$$OSNR = m^2 I_D^2 S^2(t) 10^{-\frac{Lop}{10}} / (I_{shot}^2) + (I_{th}^2) + (I_{RIN}^2) \tag{6}$$

where, I_{shot}^2, I_{th}^2 and I_{RIN}^2 are the different type of photodetector noises.

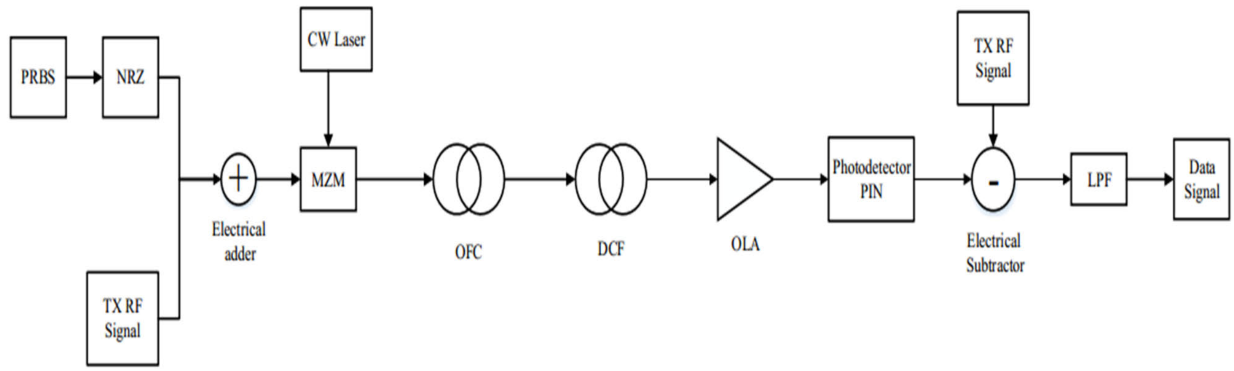

FIGURE 2. Proposed RoF system.

From eq. (6), SNR can be calculated as,

$$SNR = OSNR[1/(1+10^{\frac{10}{\propto}}/G_{op}^2] \tag{7}$$

From eq. (6) and (7), attenuation can be calculated as,

$$\propto = 10log_{10}(\frac{OSNR}{SNR}-1)G_{OP}^2 \tag{8}$$

Now, the transmission capacity analysis of radio over fiber link can be calculated as,

The material dispersion of the optical fiber can be written as,

$$\Delta\tau_{mat} = -\left(L.\Delta\lambda.\frac{\lambda}{c}\right).(d^2n/d\lambda^2) \tag{9}$$

Total dispersion of RoF communication system can be expressed as,

$$\Delta\tau_{system} = \Delta\tau_{source} + \Delta\tau_{receiver} + \Delta\tau_{mat} \tag{10}$$

The bandwidth of single mode fiber having length L_F is given by,

$$B.W_{sig} = \frac{0.44}{LF.\Delta\tau_{system}} \tag{11}$$

Considering the system working for NRZ signal,

$$B_{R(NRZ)} = \frac{0.7}{\Delta\tau_{system}} \tag{12}$$

The maximum transmission rate according to Shannon capacity theorem can be written as,

$$C = B.W_{sig}log_2(1+SNR) \tag{13}$$

Here, BER can be calculated by using following standard equation,

$$BER = 0.5[1-erf\ (0.3535(SNR)^{1/2})] \tag{14}$$

III. SYSTEM DESIGN

The proposed RoF system is illustrated in Fig. 2. The transmitter side is composed of a data source with modulation scheme, RF signal generator and Mech-Zehnder modulator. The pseudorandom bit sequence generator (PBRS) generates data bits to send them to the pulse generator to form pulses. The pulse generator's function is to convert the binary signal into electrical signal before sending it to the modulator. At the transmitting side, the signal is added with RF signal having 20 GHz frequency through electrical adder.

The modulator receives two inputs i.e., one from the adder in the form of combined electrical signals and the other from continuous wave (CW) laser source which is the carrier signal. Non-linearities of MZM are considered while simulating the environment. The signal at the output of MZM incorporates the effect of non-linear phenomenon. As the non-linearities increases with the power of the laser signal. Signal power is kept limited to avoid the non-linear phenomenon. The extinction ratio of MZM which is defined as the ratio of peak transmission power to the minimum transfer power is set to 30 dB.

CW laser operates at a frequency of 1550 nm and power of 10 dBm. The primary function of modulator is to convert the electrical signal to optical signal so that can be sent over optical fiber. The dispersion of fiber is controlled using Dispersion compensation fiber (DCF) after the optical fiber cable (OFC) of 3 km length. Optical link amplifier (OLA) is used along with the optical fiber to increase the amplitude of the transmitted signal. Operating parameters of proposed system can be seen in Table 2.

The receiver consists of PIN photodetector and a low pass Bessel filter (LPF) to reduce the sharpness of signal and for noise reduction. The signal reaches the photodetector after passing through amplifier. Pin photodetector converts the optical signal back into electrical domain. Here, this electrical signal subtracts from same RF signal which is used at the transmitting side to recover the original signal. After subtraction signal passes through LPF. The filter removes the

TABLE 2. System parameters.

Parameters	Value
Operating wavelength	1550 nm
Data rate	1 Gbps
CW laser power	10 dBm
Optical fiber cable (OFC)	3 km
DCF length	0.6 km
Attenuation	0.2 dB/km
Filter	Low pass Bessel
Amplifier gain	10 dB
Modulation Schemes	NRZ, Duobinary, CSRZ

TABLE 3. TX and RX parameters.

Parameters	Transmitter	Receiver
RF frequency	20 GHz	20 GHz
CW laser power	10 dBm	-
CW laser frequency	1510 nm	-
Responsivity	-	1 A/W
Dark current	-	10 nA

undesired components from the signal and transmits the data to the base stations.

The quality of received signal and errors in the output are determined by using eye-diagram and BER analyzers, respectively. Transmitter and receiver side parameters are mentioned in the Table 3. Initially, the input is encoded using NRZ scheme, and then duobinary and CSRZ formats are visualized to compare which format is best for RoF communication model. The use of advance modulation formats helps in reducing the network cost by permitting high bit rate at each channel and increasing spectral efficiency.

IV. RESULTS AND DISCUSSION

Simulation of the proposed model is performed using system parameters mentioned in Table 2. The results of proposed scheme are organized in following different sections:

A. WAVEFORM RECOVERY OF MODULATION FORMATS

We have compared three modulation formats in our proposed model. In all the three schemes, the signal is successfully recovered at the receiver end. The purpose of using different formats is to choose efficient modulation format for data transfer.

Initially, NRZ format is applied in the simulation model. The input message signal of NRZ format is shown in Fig. 3.

The electrical adder helps to add the NRZ signal with the RF signal. The combined signal is modulated with the CW laser source and propagates inside the optical fiber where it encounters attenuation and dispersion impairments. OLA amplifies the incoming signal and passes it to the photodetector. At this stage, an electrical subtractor isolates the received signal by subtracting it from RF signal. The noises in the received signal are reduced by using LPF. The received NRZ signal is shown in Fig. 4.

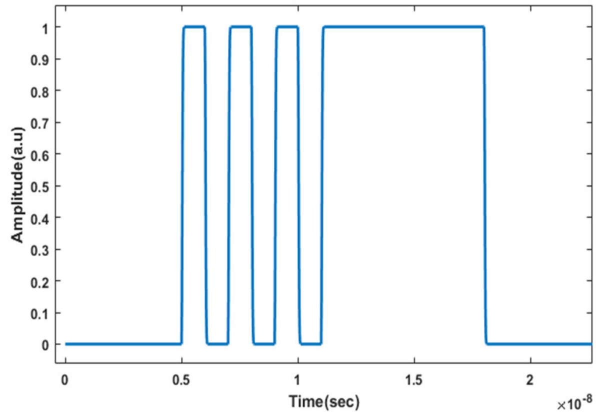

FIGURE 3. Transmitted NRZ signal.

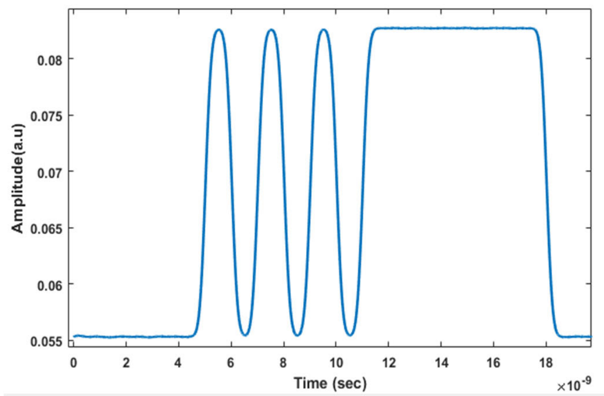

FIGURE 4. Received NRZ signal.

The frequency response of transmitted signal can be seen in Fig. 5 and 6 where RF spectrum analyzer is used to read the spectrum of the electrical signal before MZM i.e., modulation and Optical spectrum analyzer is connected after MZM when the signal is converted to optical domain after modulation. Frequency response of MZM can be seen in Fig. 6.

The output optical spectrum of Mach-Zehnder modulator has the RoF signal and its odd and even sidebands. At the photodetector side, the optical carrier and these side bands beat with each other to produce RoF signal and non-linear components.

If the dispersion is not present, even order distortion cancels out, resulting in well know transfer function of the Mach-Zehnder modulator having only odd non-linear components.

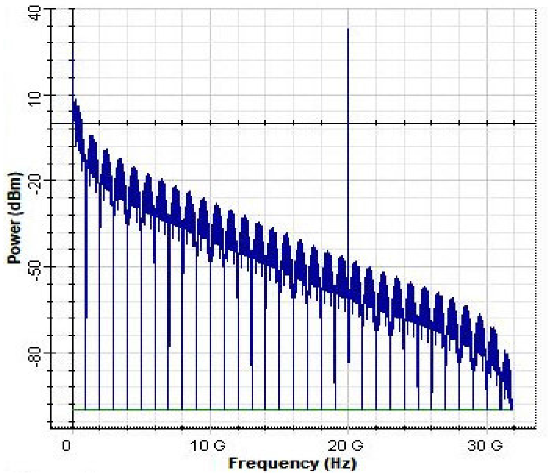

FIGURE 5. NRZ signal spectrum before modulation.

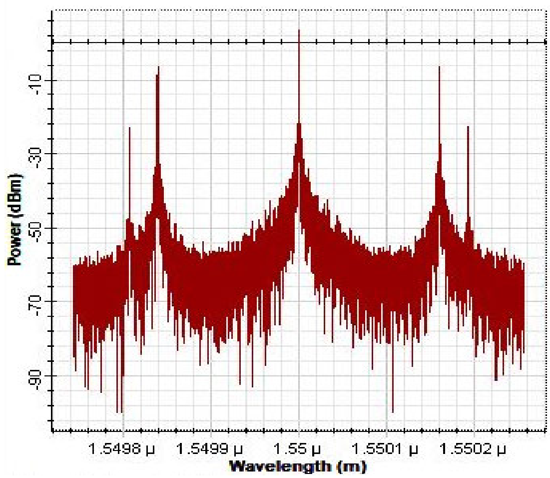

FIGURE 6. MZM output frequency response.

Considering the presence of dispersion, 2nd order distortion occurs and increases rapidly with the frequency of signal and dispersion. The effects of these non-linearities with the increase in frequency can be seen later in this section.

Similarly, other modulation schemes are implemented in our model by replacing the transmitter part with the desired modulating signal. The Duobinary signal at transmitter and receiver sides are shown in Fig. 7 and Fig. 8, respectively. The scheme after modulation of signal is same for all formats before it reaches the receiver.

The third implemented modulation scheme is CSRZ. The CSRZ signal at transmitter end is shown in Fig. 9 and the received signal is depicted in Fig. 10. Overall, NRZ signal performed best despite increasing various parameters and retained its originality at the receiver. When the modulation format becomes complex, the signal is somehow difficult to recover at the receiver due to the noise factor. Thus, CSRZ suffered badly when parameters are varied, and DB showed smaller BER and high Q-factor.

Duobinary is multilevel format which is considered as the proficient optical modulation scheme due to its greater

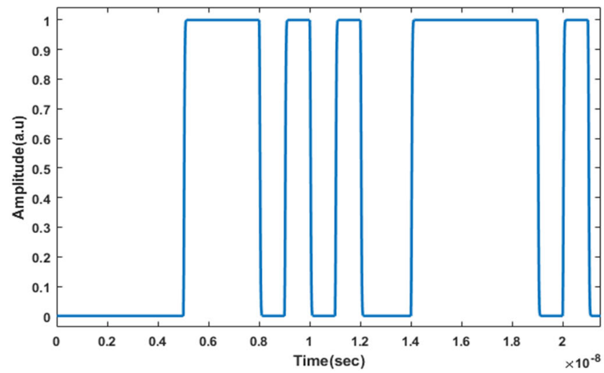

FIGURE 7. Transmitted duobinary signal.

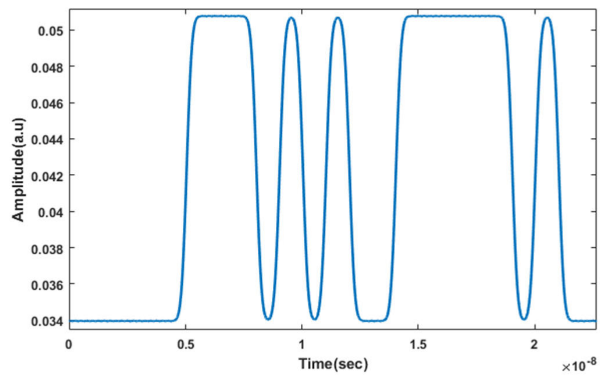

FIGURE 8. Received duobinary signal.

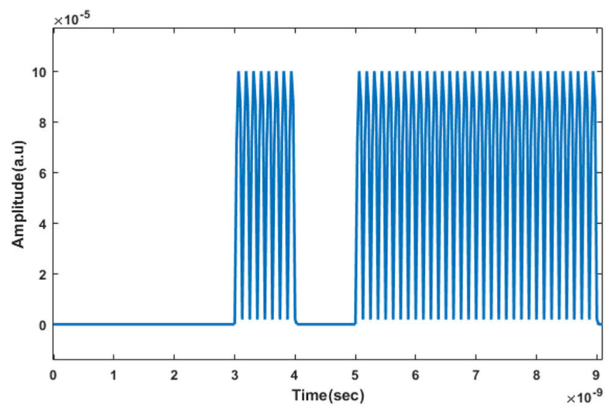

FIGURE 9. Transmitted CSRZ signal.

spectral efficiency and high efficiency [25]. However, due to greater number of signal levels compared to NRZ its complexity increases at receiver side. Further, the power penalties will be different in different types of modulation formats. For example, while using the NRZ format the power is reduced to 4.2 dBm when it is received at receiver side compared to Duobinary and CSRZ which is found to be 3.6 dBm and 2.5dBm, respectively.

B. FIBER LENGTH VS Q-FACTOR & BER

Signal quality at different fiber lengths against the three coding schemes is shown in Fig 11. Overall high Q-factor

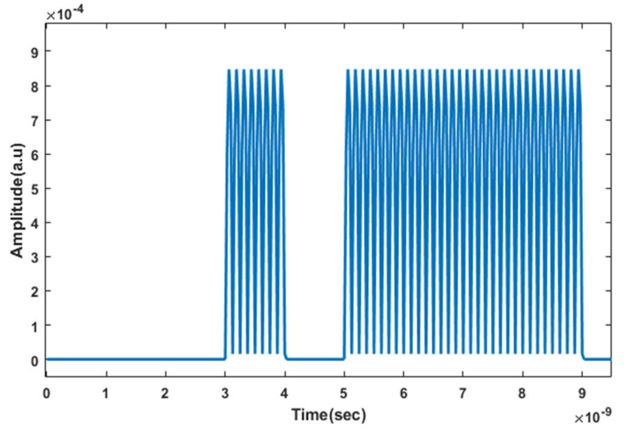

FIGURE 10. Received CSRZ signal.

can be seen at NRZ scheme while duobinary and CSRZ show significant low Q-factors. The trend clearly shows that with the increase in the fiber length, the Q-factor gradually decreases and NRZ outperforms duobinary and CSRZ.

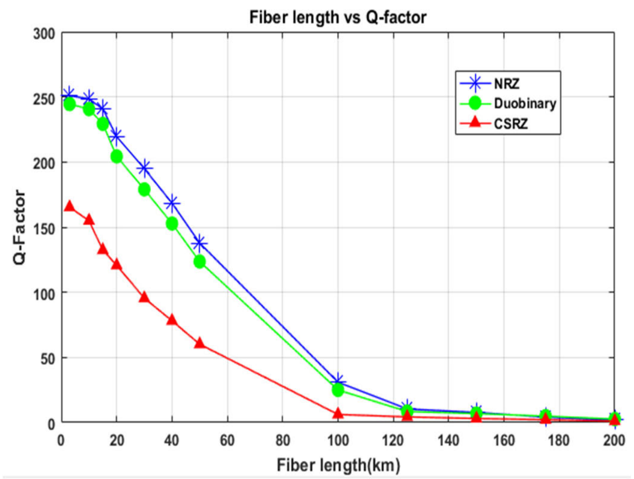

FIGURE 11. Fiber length vs Q-factor.

Fig. 12 shows the BER at different fiber lengths. BER is plotted on logarithmic scale. The graph shows that up to 60 km of optical link, the BER value lies on negative axis which means very low transmission error. At large distances the BER approaches 1 which indicates significant errors in transmission. NRZ shows better BER at small distances and even if the distance is increased it shows low error rate compared to other modulation schemes. Duobinary and CSRZ have low BER at small optical links, but their BER increases more than NRZ at same lengths of fiber.

C. DATA RATE VS Q-FACTOR & BER

A performance comparison in terms of data rate and Q-factor is illustrated in Fig. 13. A high Q-factor can be achieved at low data rates up to 6 Gbps while increasing data rates reduce

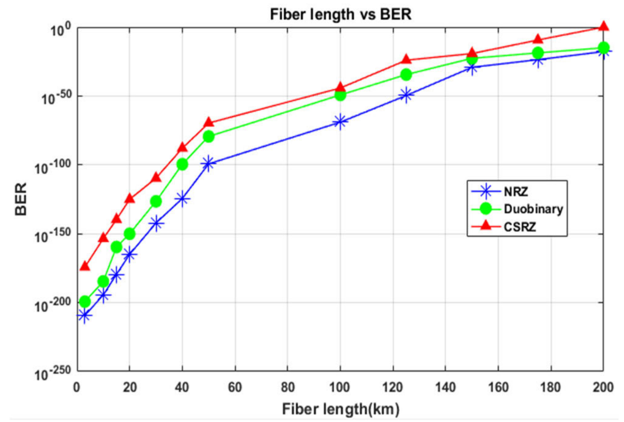

FIGURE 12. Fiber length vs BER.

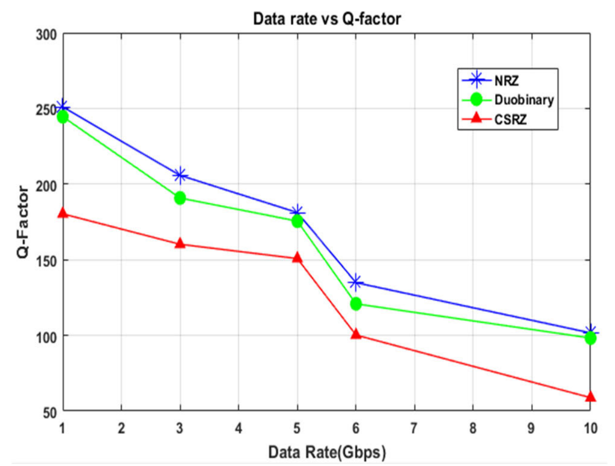

FIGURE 13. Data rate vs Q-factor.

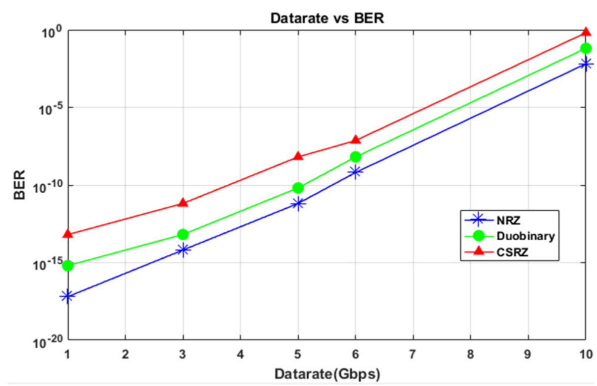

FIGURE 14. Data rate vs BER.

the quality of the signal at receiver side. NRZ shows a good Q-factor up to 10 Gbps compared to the other modulation schemes. Thus, NRZ works better in comparison to other modulation formats for high data rates.

Similarly, the data rate is plotted against BER in Fig. 14. NRZ shows less errors at small data rates. In duobinary and CSRZ, errors appear at smaller data rates but increase greatly as the data rate increases.

D. TRANSMITTING POWER VS Q-FACTOR & BER

The transmitting power shows significant changes in NRZ modulation scheme. As the power increases, the Q-factor increases dominantly. The high Q-factor is observed at 5 dBm for NRZ. In case of CSRZ, the Q-factor is unaffected by power. It shows a straight-line graph which indicates that increasing power has no effect on the results, as shown in Fig. 15.

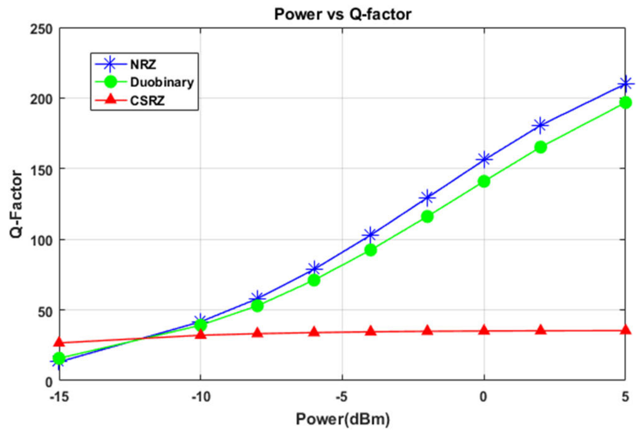

FIGURE 15. Transmitting power vs Q-factor.

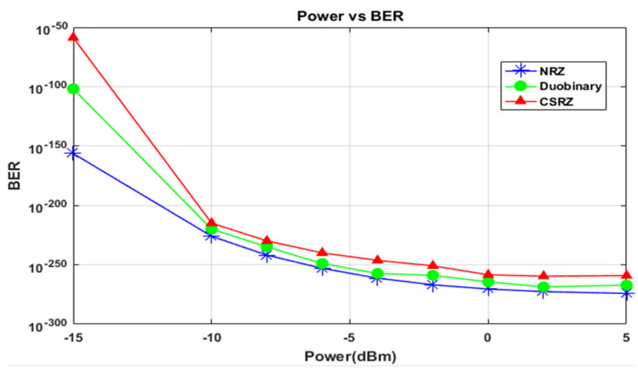

FIGURE 16. Transmitting power vs BER.

The increase in laser power decreases BER values. The BER plots are taken on logarithmic scale in our results. The plots show that CSRZ has large error values. Fig.16. shows that Duobinary has less error rate than CSRZ, also the BER decreases sharply as the laser power increases.

E. AMPLIFIER GAIN VS Q-FACTOR & BER

Optical amplifier gain is varied to analyze the quality of the received signal. The Q-factor plots are slightly varying in terms of gain. Fig. 17 shows the constant trend against the different values of gain of amplifier. NRZ has high Q-factor values while other schemes show low quality factor consistently.

Optical amplifier gain is varied to analyze its effect on BER. In Fig. 18. we can see the improvement in BER of different schemes. CSRZ has some high error values compared to NRZ and duobinary format. These schemes show almost similar trend throughout the plot. Thus overall, the BER values decreases by increasing amplifier gain up to 20 dB.

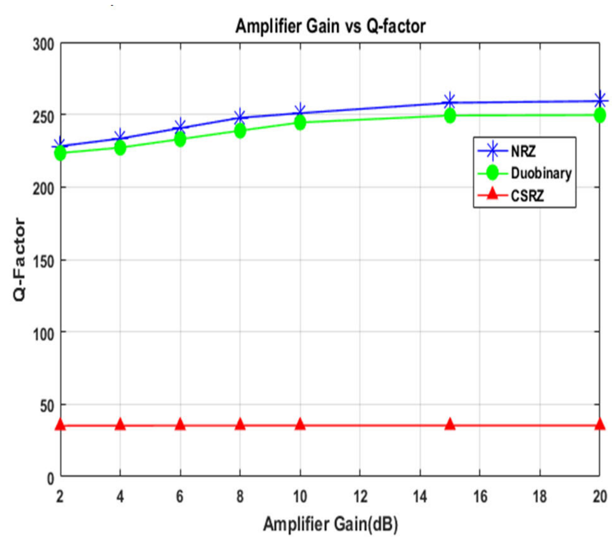

FIGURE 17. Amplifier gain vs Q-factor.

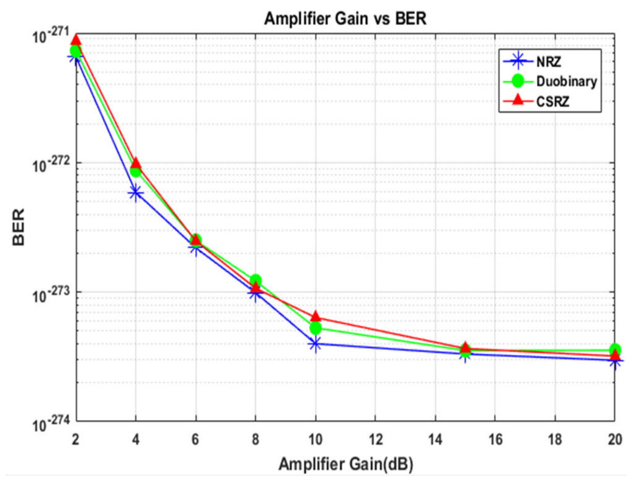

FIGURE 18. Amplifier gain vs BER.

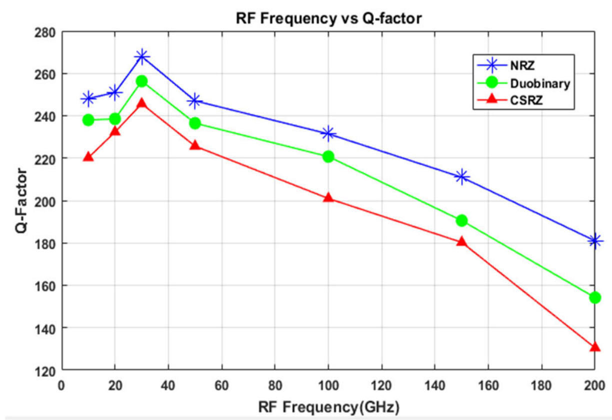

FIGURE 19. RF frequency vs Q-factor.

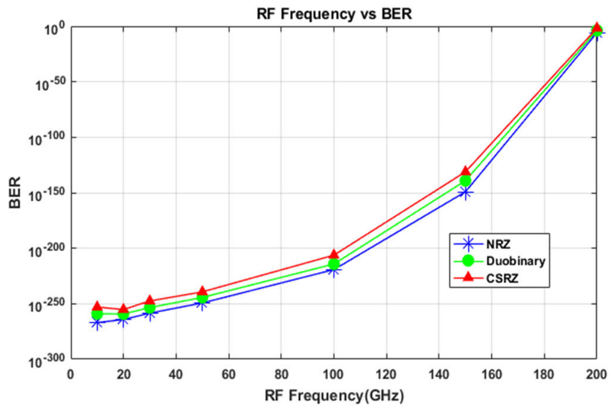

FIGURE 20. RF frequency vs BER.

F. RF FREQUENCY VS Q-FACTOR & BER

RF signal frequency is another important parameter that effects the Q-factor of the signal. It is seen to be dominant in NRZ and Duo-binary where small decrement in Q-factor is observed with the increase in frequency except from 10-30 GHz. CSRZ has low-Q factors in comparison and shows more decreasing behavior compared to the other schemes. Fig. 19 shows the illustration of the phenomena.

RF frequency is finally plotted for the BER as shown in Fig. 20. NRZ behavior is like the previous results i.e., showing minimum error values while changing frequency. CSRZ and duobinary show bit large number of errors compared to the NRZ plot. The overall trend shows that increasing frequency increases value of BER. Down Q-factor and high BER at higher frequencies is the validation of working of our proposed model.

V. CONCLUSION

Presented paper is composed of two parts. The first part comprises advantages, disadvantages challenges, and application of RoF communication system. Role of RoF in futuristic networks is also briefly described in this section. In the second part, RoF model is implemented by using licensed version of Optisystem. In the proposed model, the incoming data signal is added with RF signal during transmission while the modulated signal is subtracted from same RF signal at the receiver side. Thus, basic adder and subtractor help to avoid complex phenomena in transmission. The proposed scheme is simulated for three different modulation formats i.e., NRZ, CSRZ and duobinary to compare their performances. All the three proposed models are optimized to receive the transmitted waveforms successfully. The simulations are performed based on different parameters including data rate, fiber length, laser power, RF frequency and amplifier gain. The results are plotted by using Q-factor and BER. We found that NRZ performs exceptionally well than other schemes and provides high quality factors and low BER in different conditions. Also, significant improvement is found by increasing the amplifier gain and laser powers. In future, high order modulation formats such QAM, higher order QAM and OFDM can be implemented to enhance the usability of model.

APPENDIX

RoF	Radio over fiber
BER	Bit error rate
CW Laser	Continuous wave laser
OV	Oscilloscope visualizer
OLA	Optical link amplifier
EDA	Eye-diagram analyzer
NRZ	Non-return-to-zero
DB	Duo-binary
CSRZ	Carrier suppressed return to zero
LPF	Low pass filter
PRBS	Pseudo-random bit sequence generator
OFC	Optical Fiber Cable

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