# Performance Investigation of a High Data Rate Mode Division Multiplexed-Free Space Optics Link Under Harsh Weather Conditions

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The requirement of high data rate information transmission is rising exponentially for supporting different services including social networking, web streaming, and biomedical sensor data transmission. Such services required high channel bandwidth with secure information transmission and immunity to electromagnetic interference. Radio over free space optics (RoFSO) is witnessed as a promising technological solution to provide high data rate transmission over free space channel. We report on the design of a 2×10 Gb/s-10 GHz RoFSO transmission system using the mode division multiplexing technique and evaluate its transmission performance over varying levels of dust weather conditions. The comparison of non-return to zero (NRZ) and return to zero (RZ) binary digital optical modulation techniques is carried out in the proposed system. It is found that the proposed system using NRZ modulation serves 14.5 km transmission range; however, in the case of RZ modulation, it was restricted to 10 km for a target bit error rate (BER) of $10^{-6}$, thus resulting in a noticeable link enhancement of 4.5 km. Also, we demonstrate NRZ-based MDM-RoFSO link performance and availability in dust weather conditions using the BER, maximum reachable link range, and eye diagram as key performance parameters. We obtain a reliable transmission of 20 Gb/s-20 GHz data through HG00 and HG01 channels over a link range of 2500–108 m depending on the external dust weather condition. Furthermore, since this investigation shows the feasibility of RoFSO for small size cells, which is an essential feature of 5G mobile network, the proposed system can thus be implemented as a backhaul/fronthaul link for high-band (above 6 GHz) 5G services and for providing secure transmission of biomedical sensor data.

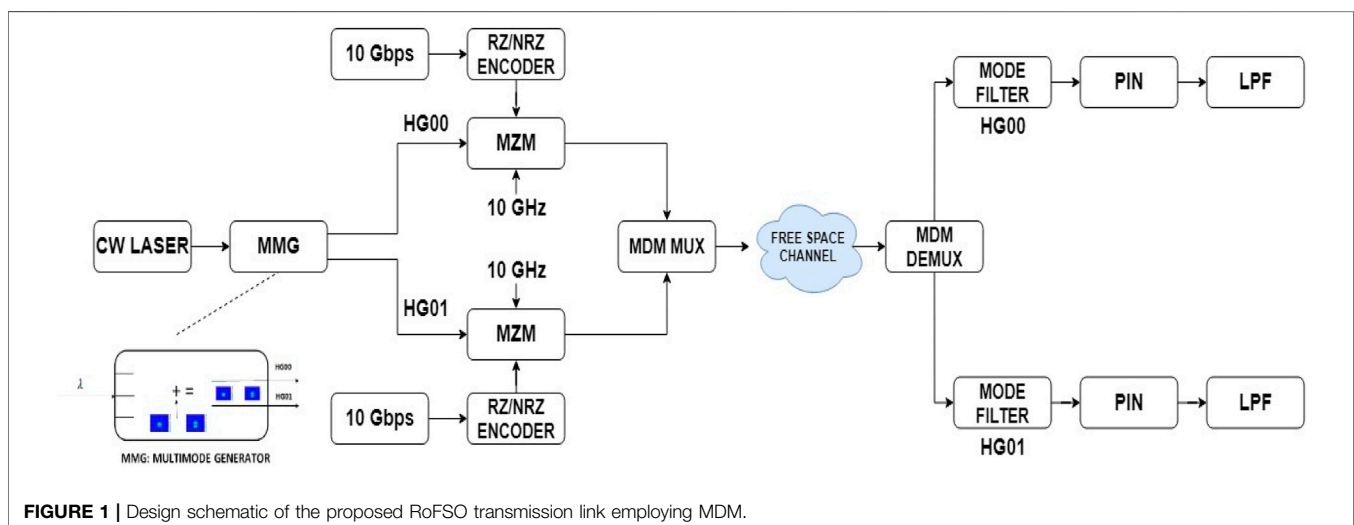**Keywords: HG, biomedical sensor data, MDM, RoFSO, 5G technology**

# INTRODUCTION

In the present-day telecommunications sector, the base transceiver station (BTS)-BTS connection is established through fiber optic trunk cables in which voice/data are transmitted at high speed using radio over fiber (RoF) technology. Also, in order to establish a BTS-user communication link, a radio-frequency (RF) network is deployed. Nevertheless, fiber installation constrictions both in urban and rural areas, excessive infrastructure costs, and hefty spectrum pricing in the case of RF technology make such approaches unattractive and unfavorable for the establishment of next-generation wireless networks. To overcome this trouble, a radio over free space optics (RoFSO) link, where the RF signal will be transmitted between BTS-BTS or BTS-user using an optical carrier (up-conversion) and air/free space as the medium, is a viable solution. RoFSO technology provides unlicensed spectrum operation, interference, and interception-free transmission within a short deployment period and little expense [1]. To enhance the spectral efficiency and information-carrying capacity of RoFSO links, the mode division multiplexing (MDM) technique is incorporated in which independent RF signals are transmitted over distinct spatial modes of a single frequency laser beam [2–6]. Recently, Satea et al. proposed that FSO systems employing multiple channels with erbium-doped fiber amplifiers (EDFAs) work efficiently under high attenuation environments such as heavy fog and dust [7]. Alaa et al. analyzed the FSO system performance in fog and sandstorm conditions by changing the operating wavelength, receiver diameter aperture, photodetector type, and the modulation technique. They found that both the dense fog and dust triggered 87 and 95% power loss, respectively, at a transmission range of 1 km [8]. Maged et al. put forth an experimental evaluation of an all-optical hybrid FSO/RF link carrying 5G signals in a
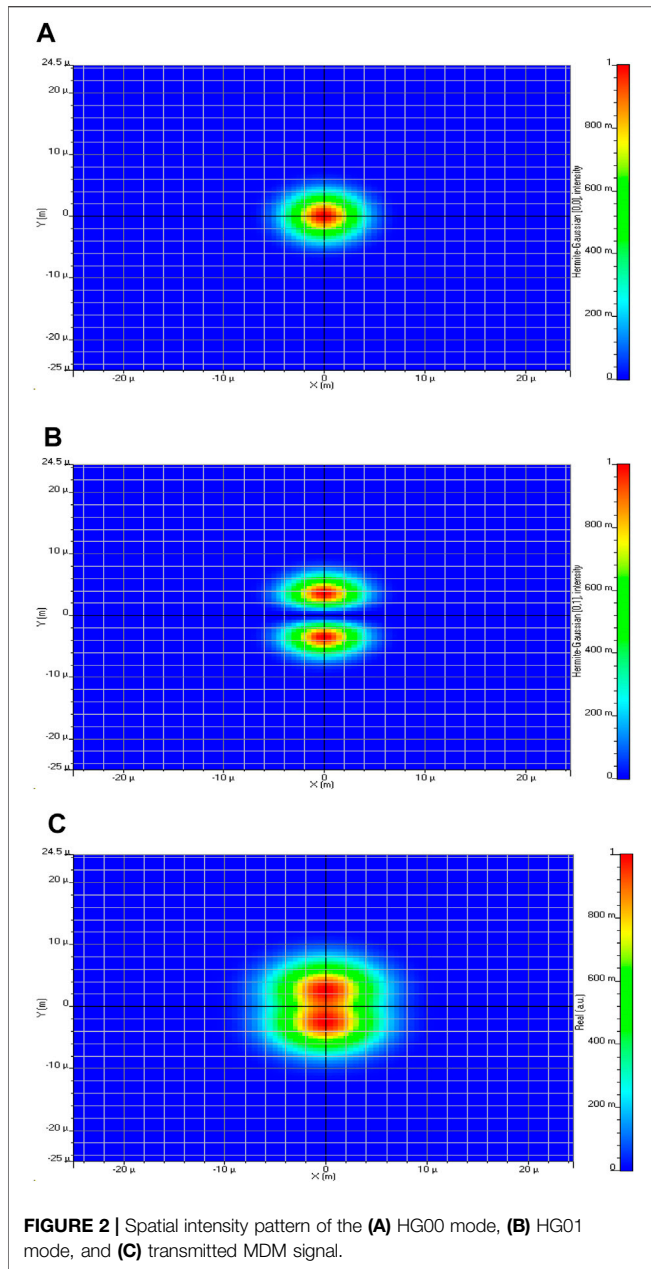
dust channel. They reported that the RF link with low bandwidth works well in dense dust and the FSO operates once the weather improves beyond a definite threshold. As a consequence, the FSO/RF parallel link can be a first-rate choice towards overcoming dust effects [9]. Matthew et al. proposed a novel visibility and dust absorption model after using visibility and absorption measurements made farther from the source (10–100 km) to demonstrate the impact of reduced dust particle size over the regional distance from the source [10]. Haichao et al. described that in addition to wavelength, particle sizes of sand and dust affect the laser beam attenuation [11]. Zabih et al. reported that the FSO link performance can be improved by increasing the launched optical power and selecting adequate line speed under sandstorm conditions [12]. The current research in RoFSO is mainly focused on fog- and smoke-induced attenuation [13–16]. Intensive investigation and modeling of the dust effects on the RoFSO channel are yet to grab the attention of researchers. Very limited or basically no attempt has been made in this course, and the development and investigation of MDM-based RoFSO transmission for dust environment has not been reported till date. In arid and semiarid regions, the effect of dust will remain paramount for any upcoming installation of the RoFSO network in 5G and smart city applications [17]. It is straightforward that the propagation prediction under dust storms regarding signal attenuation, maximum reachable distance, and error performance will be the solemn challenge for the setting up of the RoFSO communication network.

This work reports the designing and performance evaluation of an MDM-RoFSO transmission for varying levels of dust and clear climate conditions. This research article is structured as follows: *FSO Evaluation in Dust Channel* discusses the numerical model for dust storm characteristics and attenuation in FSO. *Simulation Setup Description* describes the proposed simulation

**TABLE 1 |** Dust storm classification established on a visibility basis.

| Type of dust | Severe dust storm | Dust storm | Blowing dust | Dust haze |
|---|---|---|---|---|
| **Depiction** | Dense | Moderate | Light | Very light |
| **Visibility, V (km)** | < 0.2 | 0.2–1 | 1–10 | ≤ 10 |



**FIGURE 1 |** Design schematic of the proposed RoFSO transmission link employing MDM.

**FIGURE 2 |** Spatial intensity pattern of the **(A)** HG00 mode, **(B)** HG01 mode, and **(C)** transmitted MDM signal.
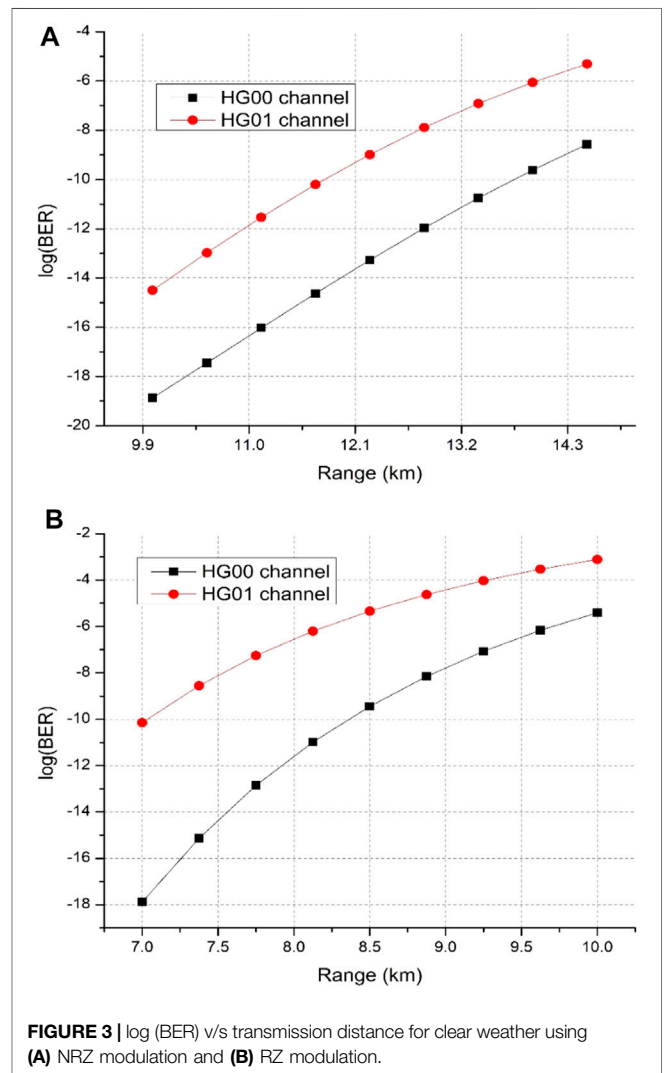
setup and parameters. *Results and Discussion* presents the simulation results, and *Conclusion* concludes the paper.
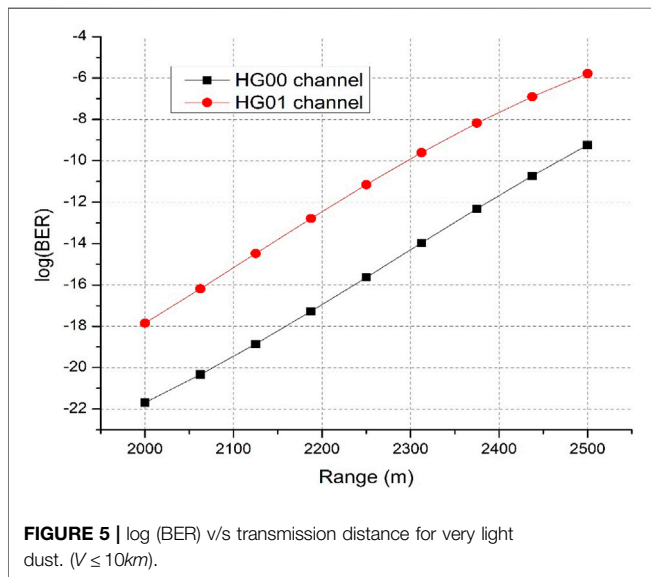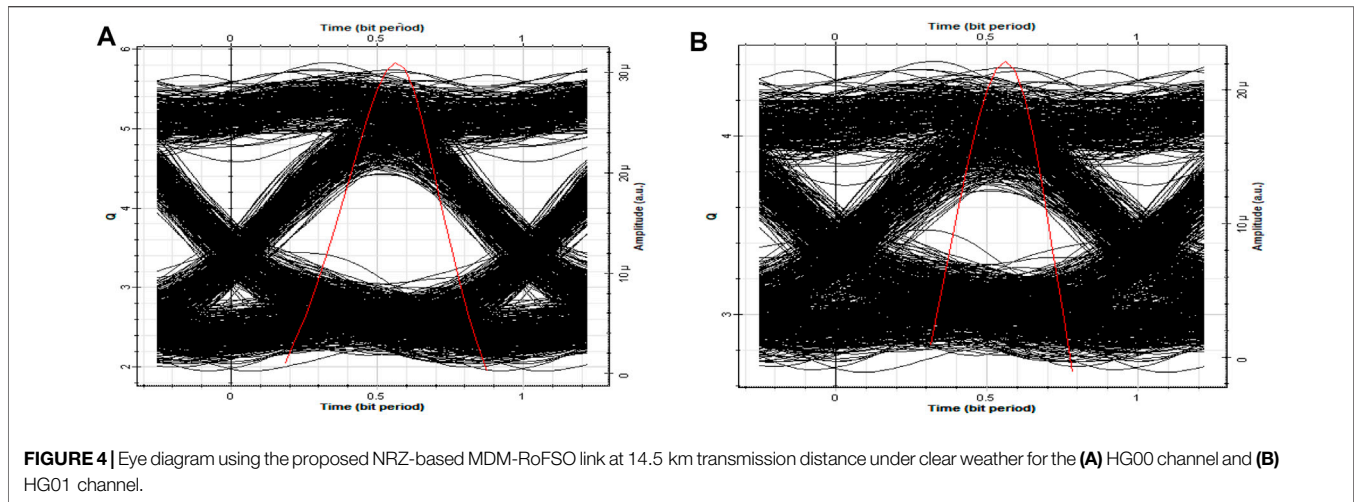
# FSO EVALUATION IN DUST CHANNEL

In FSO, the chosen signal wavelength belongs to the atmospheric transmission window which provides low molecular absorption since absorption cross-section $\sigma_a$ is negligible, that is, $\sigma_a \sim 0$ [18]. Therefore, the contribution of absorption to the total attenuation coefficient is meager in comparison to the scattering effect [19]. Different environmental factors for instance fog, rain, storm, snow, smoke, and dust causes scattering of optical beam [20, 21]. To

**TABLE 2 |** Simulation parameters considered for the proposed link design [30, 31].

| Parameter | Value |
| --- | --- |
| Operating frequency | 193.1 THz |
| Input power | 14 dBm |
| Laser linewidth | 100 e-012 MHz |
| Bit rate | 10 Gbps/channel |
| Transmitter aperture diameter | 10 cm |
| Receiver aperture diameter | 20 cm |
| Beam divergence angle | 0.25 mrad |
| PIN responsivity | 1 A/W |
| LPF cutoff frequency | 0.75×bit rate |
| Sequence length | 1,024 |
| Sample per bit | 32 |



**FIGURE 3 |** log (BER) v/s transmission distance for clear weather using **(A)** NRZ modulation and **(B)** RZ modulation.

investigate the consequences of these conditions on the FSO, one of two existing approaches can be employed. The first approach utilizes theoretic-based theorems such as Mie theory. Nevertheless, this approach involves some parameters that may not be accessible at the installation site, for example, refractive index, particle size, and distribution. [22].

**FIGURE 4 |** Eye diagram using the proposed NRZ-based MDM-RoFSO link at 14.5 km transmission distance under clear weather for the **(A)** HG00 channel and **(B)** HG01 channel.



**FIGURE 5 |** log (BER) v/s transmission distance for very light dust. ($V \leq 10 km$).

The second approach used in the literature for the calculation of attenuation in FSO for real-world applications rests on experimental remark [22]. This technique is based on experiential models established by means of visibility range statistics to identify the propagation path characteristics [23]. Link visibility information can be acquired from meteorological stations situated near the setup area. In [24], visual range is described as the distance to an entity at which the picture distinction falls to 2% of the original ocular contrast (100%) along the transmission distance usually referred to as the Koschmieder law. This 2% falloff value recognized as the visual threshold $T_{vis}$ is adopted here so as to follow the Koschmieder law as opposed to the $T_{vis} = 5\%$ considered in aviation operations [25, 26]. The visibility is computed at 550 nm wavelength since the highest solar radiation concentration occurs here. Visibility indicates the degree of sternness of the dust gale. Small visibility specifies the elevated concentration of dust elements in the free space, and vice versa.

Depending on the visibility, dust storms are classified into four groups as specified in **Table 1**. Type 1 is dust haze (very light dust) wherein widespread dust particles drift up and happen to remain suspended evenly in the atmosphere as a result of dust storm that begins at a large distance from the monitoring point. The visibility associated with this occasion is about 10 km or less. Type 2 is blowing dust (light dust) in which the dust is blown in the direction of monitoring position by the action of winds. As a result, the visibility drops between 1 and 10 km. Type 3 is dust storm (moderate dust) where strong winds bluster additional dust elements inside the observation area and the visibility decreases between 0.2 and 1 km. Finally, type 4 is severe dust storm (dense dust) which arises after a large volume of dust particles are blown by violent winds, and the visibility further drops below 0.2 km. The visibility $V$(km) in terms of $\alpha$ and $T_{vis}$ takes the form [22]:

$$V = -\frac{10 \log T_{vis}}{\alpha}, \qquad (1)$$

where $\alpha$ is the specific atmospheric attenuation coefficient expressed in (dB/km) and is determined from the light wave transmittance $T$ at 550 nm and transmission distance $d$ (km) using the Beer-Lambert law as [27]:

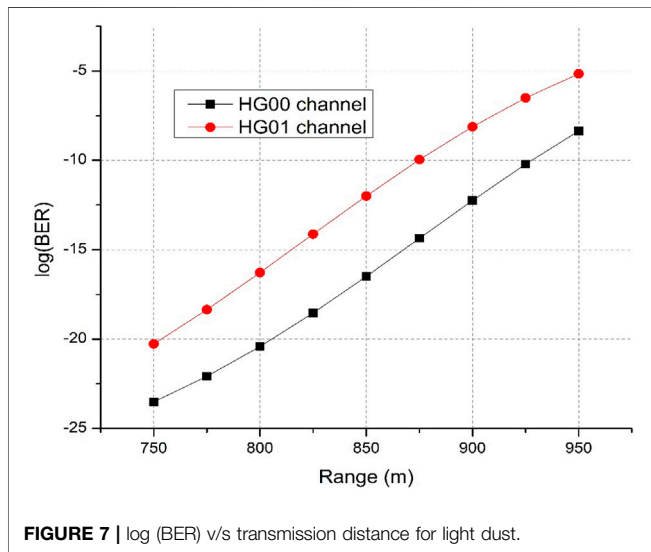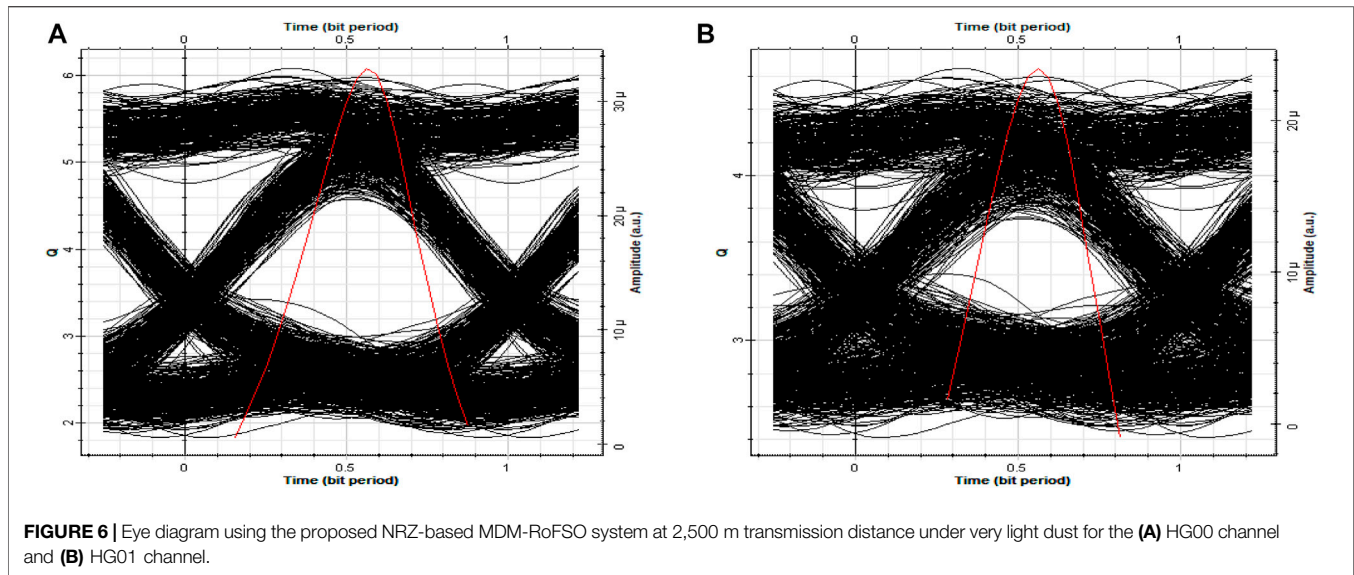$$\alpha = \frac{10 \log T}{4.343 d}. \qquad (2)$$

Moreover in [28], the FSO signal attenuation model as a function of the visibility for desert environment that is prone to frequent dust storms is obtained as:

$$\alpha = 52 \times V^{-1.05} \qquad (3)$$

**Eq. 3** holds under the condition that the operating wavelength used in FSO communication is 1,550 nm since it provides lowest atmospheric attenuation and minor absorption loss, besides its technology is mature in terms of fabrication of optoelectronic devices.

## SIMULATION SETUP DESCRIPTION

The proposed MDM-based RoFSO link setup employing RZ and NRZ binary digital optical modulation is illustrated in **Figure 1**,

**FIGURE 6 |** Eye diagram using the proposed NRZ-based MDM-RoFSO system at 2,500 m transmission distance under very light dust for the **(A)** HG00 channel and **(B)** HG01 channel.



**FIGURE 7 |** log (BER) v/s transmission distance for light dust.

which has been designed using the Optisystem™ photonic software. Two independent 10 GHz RF signals are modulated over different HG mode beams, that is, HG00 and HG01 and transported over the FSO channel. **Eq. 4** mathematically describes the intensity profiles of HG modes (**Figures 2A,B**) as [29]:

$$\psi_{p,q}(x,y) = H_p\left[\left(\frac{\sqrt{2}x}{w_{ox}}\right)\exp\left(-\frac{x^2}{w_{ox}^2}\right)\exp\left(j\frac{\pi x^2}{\lambda R_{ox}}\right)\right]$$
$$\times H_q\left[\left(\frac{\sqrt{2}y}{w_{oy}}\right)\exp\left(-\frac{y^2}{w_{oy}^2}\right)\exp\left(j\frac{\pi y^2}{\lambda R_{oy}}\right)\right], \quad (4)$$

where $p$ and $q$ denote mode dependencies on the $x$ and $y$ axes, R signifies the radius of curvature, $w_o$ indicates the spot size, and $H_p$ and $H_q$ represent Hermite polynomials. In our proposed design, a
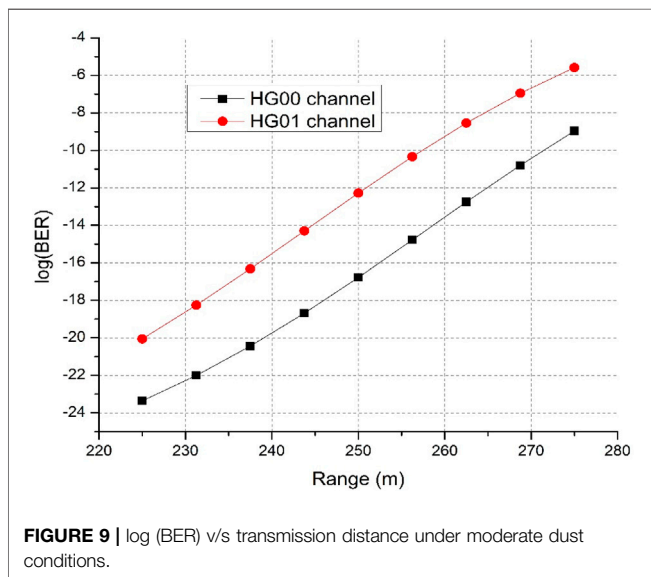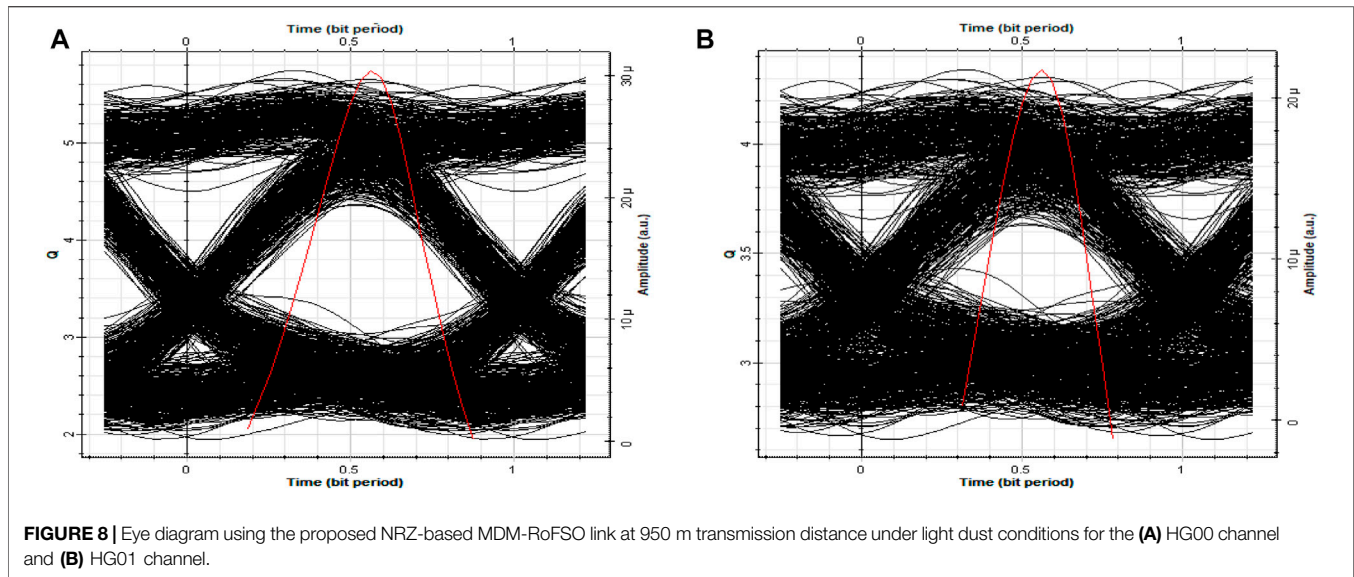
continuous wave (CW) laser at 193.1 THz together with an MMG is used to generate two different HG modes. **Figure 2** depicts the spatial profile of HG modes. **Figure 2C** demonstrates the spatial profile of the 2×10 Gb/s-10 GHz MDM-RoFSO transmitted signal.

A 10 Gb/s information-carrying signal is produced by a pseudorandom bit sequence generator (PRBS) for distinct channels and encoded using RZ/NRZ schemes. In RZ-encoded signal, bit "1" is transported by an optical pulse with half bit period. Whereas in NRZ-encoded signal, bit "1" is transported through an optical signal of entire bit period, while in place of bit "0", no optical signal is conveyed. A Mach–Zehnder modulator (MZM) is utilized to superimpose the encoded information onto a 10-GHz RF signal and a distinct HG mode. This information signal is subsequently communicated into the FSO channel through HG00 and HG01 modes of the 193.1 THz frequency channel.

Mathematically, the signal received after FSO transmission can be modeled as [32]:

$$P_{rx} = P_{tx}\left[\frac{D_{rx}^2}{(D_{tx} + \theta d)^2}\right]10^{-\alpha d/10}, \quad (5)$$

where $P_{rx}$ and $P_{tx}$ denote the received and transmitted optical power, respectively, $D_{rx}$ and $D_{tx}$ denote the receiver and transmitter antenna diameter, and $\theta$ is the divergence angle. The system parameters considered in the proposed link design are listed in **Table 2**. The coefficient of atmospheric attenuation for clear sky is 0.14 dB/km and 6.73 dB/km for very light dust, 25.11 for light dust, 107.66 dB/km for moderate dust, and 297.38 dB/km for dense dust [33]. At the receiver end, separates modes are filtered using a mode filter [34, 35]. A spatial positive-intrinsic-negative (PIN) photodiode converts the received optical signal into its electrical equivalent which is followed by low-pass filtering to retrieve the original baseband signal.

FIGURE 8 | Eye diagram using the proposed NRZ-based MDM-RoFSO link at 950 m transmission distance under light dust conditions for the (A) HG00 channel and (B) HG01 channel.



FIGURE 9 | log (BER) v/s transmission distance under moderate dust conditions.

## RESULTS AND DISCUSSION

Firstly, we compare the performance of NRZ and RZ modulation-based MDM-RoFSO link under a clear climate. Secondly, we investigate the proposed MDM-RoFSO link utilizing NRZ modulation for four different dust storm conditions. The performance analysis has been carried out with regard to BER, transmission range, and eye diagram.

**Figure 3** presents RZ/NRZ-MDM-RoFSO transmission system performance in terms of BER and range under clear weather conditions where each HG mode (HG00 and HG01) carries independent 10 Gb/s-10 GHz information. Though BER of the system degrades with increasing transmission distance for both the channels, it can be found from **Figure 3A**, using NRZ modulation scheme, the maximum achievable link range is

14.5 km while it decreases to 10 km for RZ modulation in **Figure 3B** under acceptable performance criteria [log (BER) $\approx -6$]. This concludes that NRZ modulation outperforms RZ modulation by a notable increment of 4.5 km FSO link range. Henceforth, we have implemented the NRZ modulation format in the succeeding analysis. The clear eye diagrams at 14.5 km for both the spatial channels as shown in **Figure 4** display a reliable transmission of 20 Gb/s-20 GHz information signal.

To determine how far and well the proposed link can function under four different dust storm situations, we draw the log of BER versus maximum reachable distance graphs. In addition, to demonstrate the reliability of our observations, we report the eye diagrams using the proposed system for each maximum reachable range with regard to specific dust conditions for both the channels.

**Figure 5** shows a log of BER versus range curve under very light dust conditions, that is, $V \leq 10 km$. It is evident that the BER performance of the received signals deteriorated from a log (BER) of $-21.69$ at 2000 m to $-9.24$ at 2,500 m for the HG00 channel and $-17.85$ at 2000 m to $-5.79$ at 2,500 m for the HG01 channel, respectively. **Figure 6** displays the eye diagram of the signals received from the HG00 and HG01 channels at a transmission range of 2,500 m under very light dust circumstances for the proposed design. The outcomes from **Figures 5**, **6** show 20 Gb/s-20 GHz information signal transmission around a distance of 2,500 m under very light dust conditions within standard performance criteria of log (BER) $\approx -6$ and Q factor $\approx 6$.

The proposed NRZ-based MDM-RoFSO system performance in light dust conditions (i.e., $1 km < V < 10 km$) as a function of the log (BER) and transmission range is presented in **Figure 7**. It can be found that the BER performance of the received signals declines from log (BER) of $-23.51$ at 750 m to $-8.36$ at 950 m for the HG00 channel and $-20.27$ at 750 m to $-5.16$ at 950 m for the HG01 channel, respectively. **Figure 8** displays an eye diagram of the signals
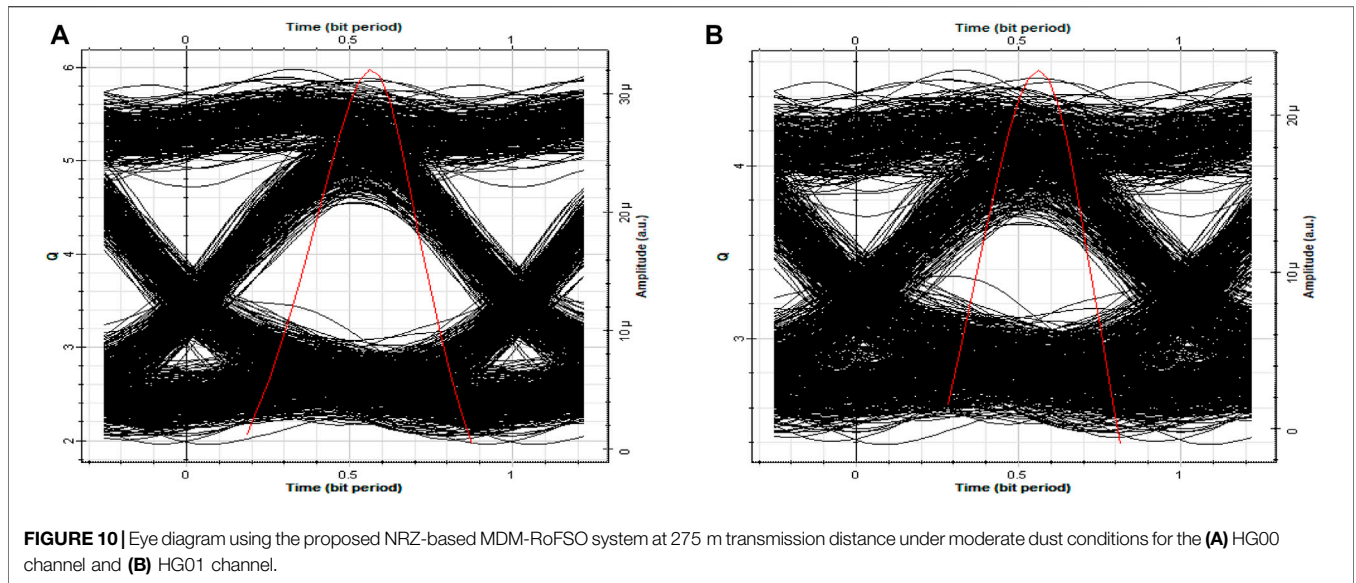
**FIGURE 10** | Eye diagram using the proposed NRZ-based MDM-RoFSO system at 275 m transmission distance under moderate dust conditions for the **(A)** HG00 channel and **(B)** HG01 channel.
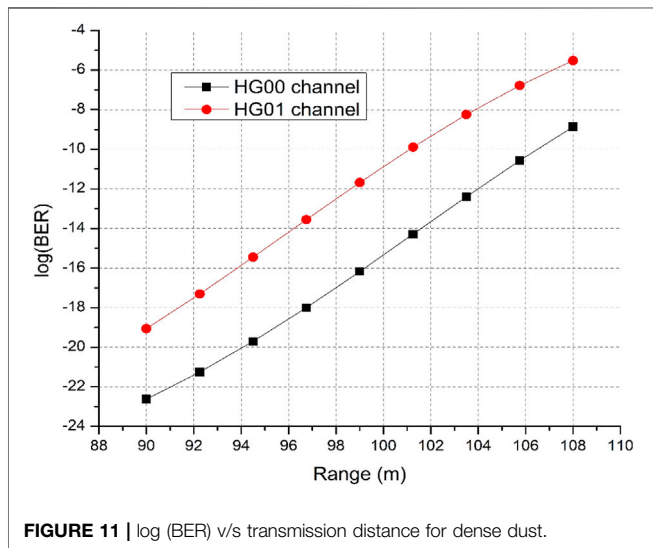


**FIGURE 11** | log (BER) v/s transmission distance for dense dust.
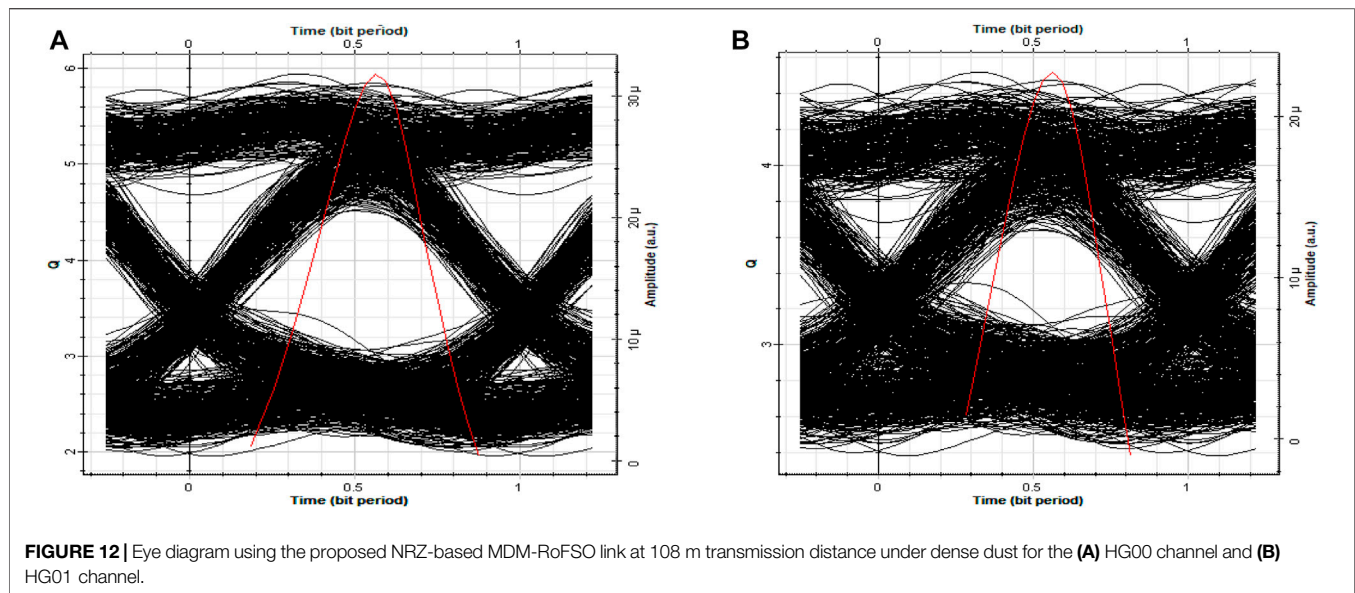
received at 950 m for light dust conditions. The outcomes from **Figures 7**, **8** show 20 Gb/s-20 GHz information signal transmission around a distance of 950 m under very light dust conditions within standard performance criteria.

**Figure 9** illustrates the log (BER) versus range graph under moderate dust conditions (i.e., 0.2 km < V < 1 km). As can be seen, the BER performance of the received signals reduces from a log (BER) of −23.36 at 225 m to −8.96 at 275 m for the HG00 channel and −20.05 at 225 m to −5.59 at 275 m for the HG01 channel, respectively. **Figure 10** depicts the eye diagram of the two 10 Gb/s-10 GHz received signals from the HG00 and HG01 channels at a transmission distance of 275 m under moderate dust. The outcomes outlined in **Figures 9**, **10** reveal 20 Gb/s-20 GHz data transmission at 275 m in moderate dust situation with log (BER) ≈ − 6 and Q factor ≈ 6.

The transmission performance of the proposed system under dense dust (i.e., V < 0.2 km) as a function of the log (BER) and transmission range is shown in **Figure 11**. As can be noticed, the BER performance of the received signal deteriorates from a log (BER) of −22.62 at 90 m to −8.88 at 108 m for the HG00 channel and −19.06 at 90 m to −5.52 at 108 m for the HG01 channel, respectively. **Figure 12** displays the eye diagram of the two signals transported over HG00 and HG01 channels at a distance of 108 m for a dense dust scenario. As follows from **Figures 11**, **12**, 20 Gb/s-20 GHz information is transported at 108 m under dense dust within acceptable performance limits using the proposed system. Nonetheless, there is no prominent increment in the maximum link reach under dense dust situations. Fortunately, the incident

**TABLE 3** | Comparison of the transmission performance of the proposed system with recent works.

| Parameter | Reference [7] | Reference [23] | Reference [33] | Proposed work |
|---|---|---|---|---|
| Transmission method | OOK-based FSO link with MIMO and EDFA preamplifier | OOK-based FSO link with single-channel transmission | OOK-based WDM-FSO Link | OOK-based FSO Link employing MDM |
| Data rate | 2.5 Gbps | 2.5 Gbps | 1 Gbps | 20 Gbps |
| Transmission power | 160 mW (22 dBm) | 22 dBm | 50 dBm | 14 dBm |
| Channel conditions and maximum range | Moderate dust- 2.3 km Heavy dust-380 m | Light dust- 1 km Moderate dust- 800 m Heavy dust < 200 m | Very light dust-13.5 km Light dust-4.05 km Moderate dust-1.05 km Heavy dust-0.405 km | Very light dust-2.5 km Light dust- 950 m Moderate dust-275 m Heavy dust- 108 m |

**FIGURE 12 |** Eye diagram using the proposed NRZ-based MDM-RoFSO link at 108 m transmission distance under dense dust for the **(A)** HG00 channel and **(B)** HG01 channel.

of dense dust waves is unusual and accounts for just 0.17% of the year time [36].

Table 3 compares the transmission performance of the proposed system with recent works and demonstrates that the proposed system achieves higher information capacity. The higher range in recent works can be attributed to the fact that the authors have considered higher transmission power, that is, 22 dBm (Ref [7, 23]) and 50 dBm (Ref. [33]), as compared to 14 dBm in this work.

## CONCLUSION

RoFSO transmission systems integrated with MDM technology can provide a viable solution for providing secure biomedical sensor data transmission in medical facilities. In this work, an NRZ/RZ digital optical modulation schemes based MDM-RoFSO transmission system is proposed and investigated. The outcomes presented demonstrate that NRZ modulation performs significantly better in terms of providing extra 4.5 km coverage as compared to the RZ modulation format. We first investigated the performance reliability and availability of a NRZ-based MDM-RoFSO transmission system in a dust environment. The results obtained show the likelihood of establishing short FSO networks under light and moderate dust circumstances. Nevertheless, rarely encountered dense dust scenarios can significantly affect the performance of MDM-RoFSO links. Additionally, because the 5G network uses ultra-compact

cells with modest separation, the proposed NRZ-based MDM-RoFSO link can prove to be a promising substitute to fiber cables in the fronthaul and backhaul sectors of next-generation wireless networks. In future works, the transmission capacity of the proposed system can further be enhanced by incorporating polarization multiplexing along with higher-order modulation schemes.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, and further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

MS: Conceptualization, methodology, investigation, writing—original draft, supervision, resources, project administration. SP: Methodology, investigation, writing—original draft, supervision. S: Methodology, investigation, data curation, visualization. SD: Investigation, data curation, writing—original draft. R: Investigation, data curation, visualization. AG: Writing—review and editing, validation, conceptualization. AM: Investigation, data curation, visualization. AM: Writing—review and editing, validation, conceptualization.

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