40Gbit/s-80GHz hybrid MDM-OFDM-Multibeam based RoFSO transmission link under the effect of adverse weather conditions with enhanced detection

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In this work, we report the modeling and performance investigation of a novel hybrid MDM-OFDM-Multibeam based Radio over Free Space Optics (RoFSO) transmission link. The performance of the proposed link has been compared using single beam and 4-beams transmission under the effect of heavy fog conditions. We have demonstrated simultaneous transmission of two 20Gbit/s-40GHz information channels using distinct spatial Hermite Gaussian mode at 2000m link range. An improvement of 18 dB in SNR and 22 dB in total received optical power by using the proposed 4-beams transmission link design can be observed from the numerical results. Also, an improved performance of the proposed link using a Square root module (SRm) at the receiver terminal to maximize the range has been investigated. The numerical results report that the maximum link range with acceptable performance increases from 2000 m to 4000 m under heavy fog conditions by using the proposed enhanced detection technique.

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1. Introduction

The increasing trend towards cloud computing, growth in the smart phones adoption, and use of various bandwidth consuming multimedia applications like video conferencing, live streaming, high-speed internet etc. have led to an exponential growth in the mobile data traffic in the last decade and is expected to rise tenfold in the next few years [1]. The rise in the number of mobile users and growing channel bandwidth requirement has challenged the effective utilization of limited radio frequency (RF) spectrum among different mobile operators and has resulted in fierce candidacy for information bandwidth [2, 3]. Recently, Radio over Free Space Optics (RoFSO) technology is proposed by many researchers to tackle the spectrum scarcity challenges. In RoFSO technology, the mobile user transmits RF information signals at a high-speed using optically modulated carrier signals which do not require any spectrum licensing or expensive laying out of fiber cables, thus escalating the deployment of wireless network framework [4]. RoFSO links can be deployed as the backbone for existing wireless networks as they capitalize on a completely different range of the electromagnetic spectrum, thus relieving the problem of RF spectrum congestion in wireless networks. RoFSO links can be used by the present mobile infrastructure to (a) transmit RF information signals at high-speed (b) lower attenuation losses (c) less power consumption and for other processes like coding, multiplexing, RF up-down conversion, and mobile handoff [5-6]. Recent developments in RoFSO technology includes statistical modeling [7-8] and experimental measurements [9] under different atmospheric weather conditions and turbulence effects. In spite of many advantages of RoFSO links, external environmental conditions such as signal power absorption, scintillation, scattering, beam wandering, turbulence etc degrade the system performance. One of the most important factors which degrades the quality of optical information signal and limits the link reach is the atmospheric attenuation due to different weather conditions.

Orthogonal frequency division multiplexing (OFDM) is another information transmission technology which utilizes multiple orthogonal sub-carriers to transmit information at high speed with low inter-symbol interference [10]. In order to boost the RoFSO link information transmission rate, phase multiplexing [11], intensity multiplexing [12], and wavelength multiplexing [13] have been investigated. Mode division multiplexing (MDM) technique capable of transmitting multiple data signals simultaneously using a single wavelength channel and exploiting different Eigen modes of a continuous wave laser generated using modal decomposition method [14], spatial light modulators [15], photonic crystal fiber [16], optical signal processing [17] has been reported in recent works. The work in [18] reports the performance investigation of Laguerre Gaussian (LG) modes in a hybrid wavelength division multiplexing (WDM)-MDM based RoFSO transmission system and compared its performance using duobinary modulation and alternate mark inversion (AMI) schemes. The performance investigation of dense wavelength division multiplexing

(DWDM)-passive optical network (PON) architecture for a MDM based Fiber-to-the-Home application has been discussed in [19]. In another work [20], the authors discuss the application of MDM in few mode fiber for three channel differential phase shift keying (DPSK) based triple play services. In more recent work [21], reports the simulative comparison of different amplifier configurations in a MDM based multimode fiber link. The authors report that inline amplifier configuration performs the best followed by booster amplifier and pre-amplifier. The authors in [22] report a doublet lens scheme based 100 m-320Gbit/s MDM-FSO transmission link. The performance of nine channel MDM based multimode fiber link incorporating linear polarized (LP) modes is simulative demonstrated in [23]. Here, in [24] discusses the simulative investigation of 10Tbit/s LP-MDM-WDM multimode fiber link for short reach applications. In another work [25], a high-speed MDM-RoFSO transmission link is developed and analyzed under different weather conditions using Hermite Gaussian (HG) modes. The performance investigation of three channel MDM based RoFSO link incorporating LG modes with photonic crystal fiber (PCF) based mode selector has been discussed in [26]. The simulative investigation of two channel MDM-RoFSO link with solid core PCF has been reported in [27]. The performance of non-return to zero-DPSK (NRZ-DPSK) based RoFSO transmission link using MDM technique has been investigated in [28]. The optimization of AMI-MDM-RoFSO link under the effect of different weather conditions has been investigated in [29]. While the authors in [18-29] have reported the development and analysis of MDM-RoFSO transmission links under different environmental conditions, it is still a vastly unexploited area.

The principal contribution of this work is as follows- (1) designing and performance analysis of a novel RoFSO transmission link with high-speed and long-haul transmission capabilities by incorporating hybrid MDM technique with OFDM and Multibeam concept under the effect of heavy fog conditions (2) maximizing the achievable link range for adverse conditions by incorporating the proposed improved detection at the receiver (3) demonstrating the superiority of the proposed system by comparing it with recent works. The remainder of the paper is organized as follows- Section 2 presents link design and simulation parameters, results and discussions are reported in Section 3 followed by the conclusion in Section 4.

2. System design and simulation parameters

Fig. 1 shows the schematic design of the proposed RoFSO link incorporating hybrid MDM and OFDM techniques along with 4-beam transmission for improved performance.

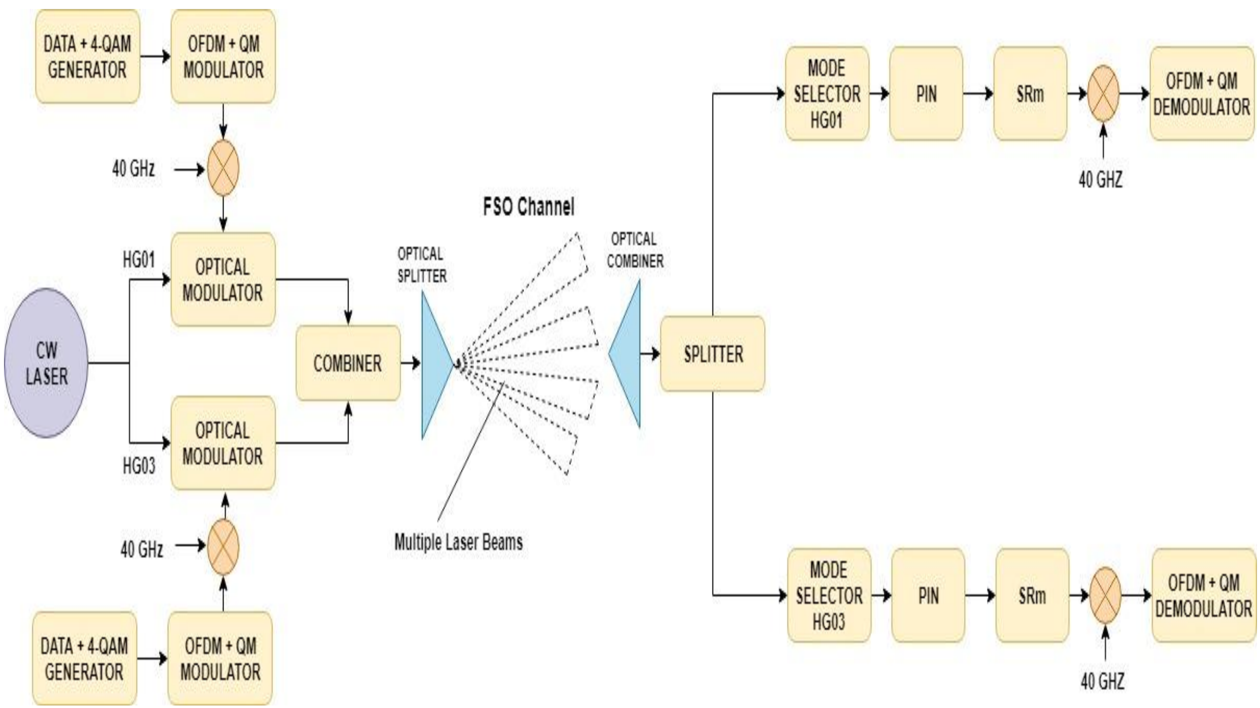


Fig. 1. MDM-OFDM based RoFSO link using 4-beam transmission (color online)

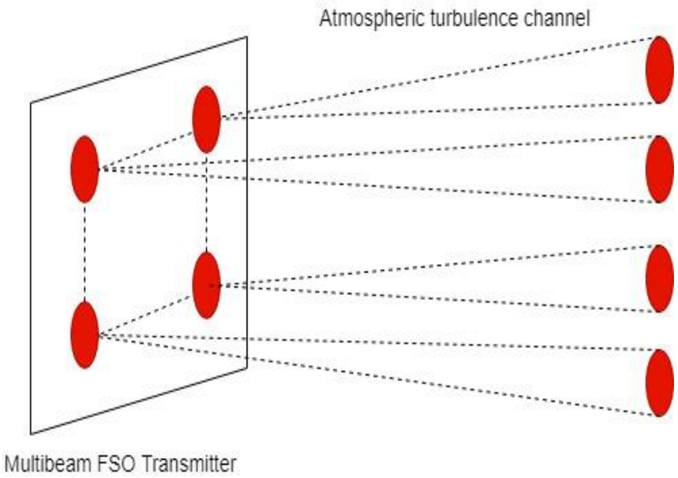


Fig. 2. Concept of 4-beam transmitter

Two independent information signals each carrying 20Gbit/s-40GHz data are transmitted over two distinct HG modes, channel 1 with HG01 mode and channel 2 with HG03 mode. The HG modes are mathematically described as [30]:

$$\varphi_{m,n}\,(r,\emptyset) = H_m\left(\frac{\sqrt{2}x}{\omega_{0,x}}\right)\exp\left(-\frac{x^2}{\omega_{ox}^2}\right)\exp\left(j\frac{\pi x^2}{\lambda R_{ox}}\right) \times H_n\left(\frac{\sqrt{2}y}{w_{o,y}}\right)\exp\left(-\frac{y^2}{w_{oy}^2}\right)\left(j\frac{\pi y^2}{\lambda R_{oy}}\right) \quad (1)$$

where m is the x-polarization axis mode dependency, n is the y-polarization axis mode dependency, the radius of curvature is denoted by R, the spot size at the waist of the beam is denoted by w_o, and $H_m\; and\; H_n$ denotes the Hermite polynomials. In this work, we have excited different spatial modes using a continuous wave (CW) laser and a mode generator followed by vortex lens. For each channel, 20Gbit/s information is generated using a 4-quadrature amplitude modulator (QAM) having 2-bits per symbol which is further OFDM modulated with 32 prefix points, 512 sub-carriers and 1024 FFT points which is then modulated using a 7.5 GHz quadrature modulator (QM) at 40 GHz. This signal is then optically modulated using a 10 dBm CW laser at 193.1 THz and a dual-electrode Mach-Zehnder Modulator (DEMZM). Each OFDM modulated signal is then combined using a combiner. This signal is then directed towards an optical splitter which splits the information signal into 4-beams as shown in Fig. 2. The FSO link is represented as [31]:

$$P_{Received} = P_{Transmitted}\left(\frac{d_R^2 Z}{(d_T + \theta Z)^2}\right)10^{-\sigma Z/10} \quad (2)$$

where the diameter of the receiver telescope lens is denoted by d_R, diameter of the transmitter telescope lens is denoted by d_T, the beam divergence angle is denoted by θ, link range is denoted by Z, and attenuation by σ. In our proposed study, simulation parameters are taken according to practical FSO links as reported by the authors in [25-29]. In our proposed 4-beams system, the signal from the output of the DEMZM is split into 4-beams using an optical splitter which are then transmitted using optical transmitter (Tx) lens. At the receiver terminal, the receiver lens (Rx) are placed close to each other and also due to the divergence of the transmitted beams, each beam is being received by four lens at the receiver terminal thus making a total of 16 paths carrying the information signal in the FSO channel. The independently transmitted multiple beams overlap with each other over the link distance, thus producing a strong signal with high-power at the receiver terminal [32, 33]. At the receiver terminal, a mode selector is used which separates different modes. The authors in [34] discuss the principle of mode selector. Further, to convert the information beam from optical to electric signal, a PIN photodiode with 0.8 A/W responsivity and 10 nA dark current is deployed. The demodulation section consists of a QAM demodulator utilizing 2-bits/symbol and an OFDM demodulator. The information signal is recovered using a QM decoder. The specific attenuation due to fog can be determined using the following equation [35]:

$$\beta_{fog}\,(\lambda) = \frac{3.91}{V}\left(\frac{\lambda}{550}\right)^{-p} \quad (3)$$

where V (km) represents range of visibility, λ (nm) is the wavelength and p is the distribution coefficient of scattering and can be determined by Kim model as [36]:

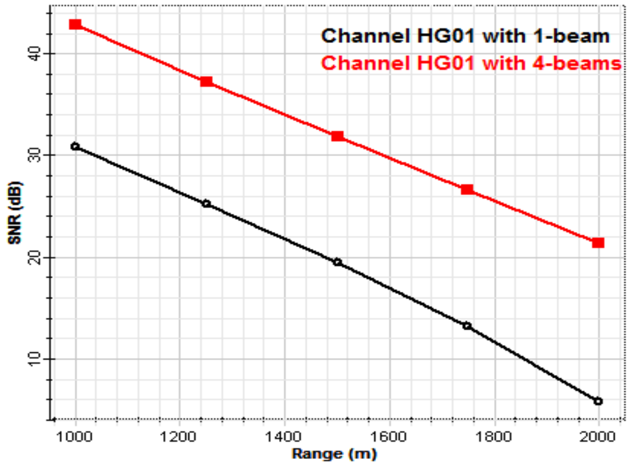
$$p = \begin{cases} 1.6 & V > 50 \\ 1.3 & 6 < V < 50 \\ 0.16\,V + 0.34 & 1 < V < 6 \\ V - 0.5 & 0.5 < V < 1 \\ 0 & V < 0.5 \end{cases} \quad (4)$$

Using the above equations, the heavy fog attenuation coefficient is calculated to be 22 dB/km [25-29].

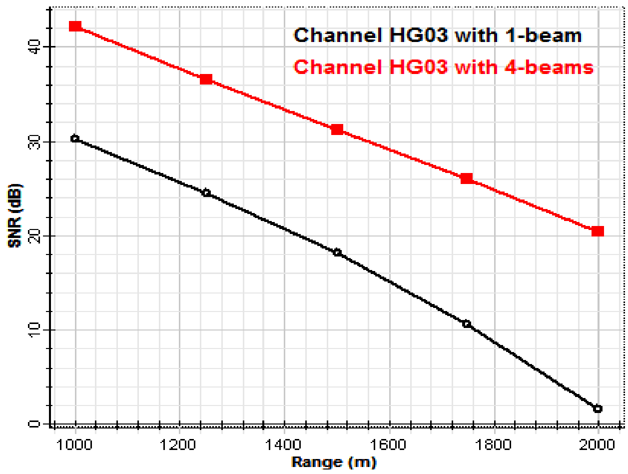
3. Results and discussion

The numerical results of the simulation of the proposed link is illustrated and analyzed in this section. For better emphasis and clarity of the reader, the first section discusses the proposed link performance without taking improved detection technique into consideration. The improved performance using SRm is presented in the later section.

Fig. 3 and 4 illustrates the proposed link performance investigation using signal-to-noise ratio (SNR) plots and total optical power at the receiver terminal plots for different spatial channels with increasing range under heavy fog.

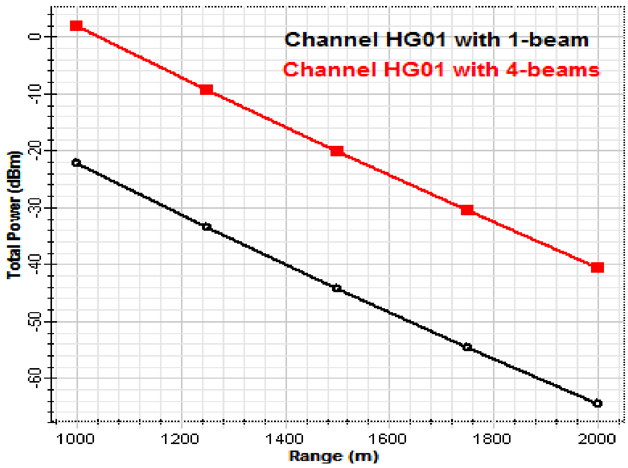


(a)

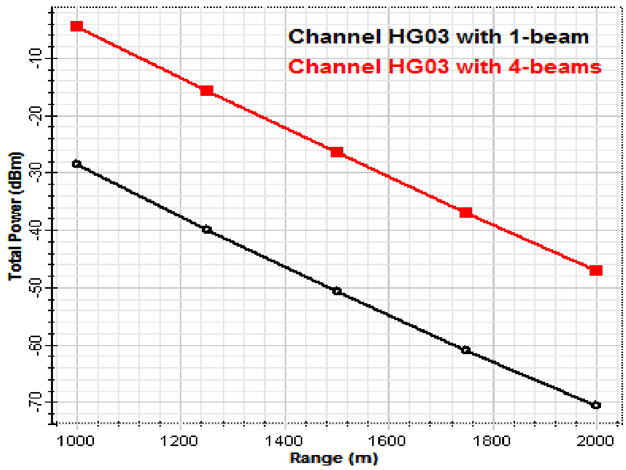


(b)

Fig. 3. Measured SNR for (a) Channel 1 (b) Channel 2 (color online)



(a)

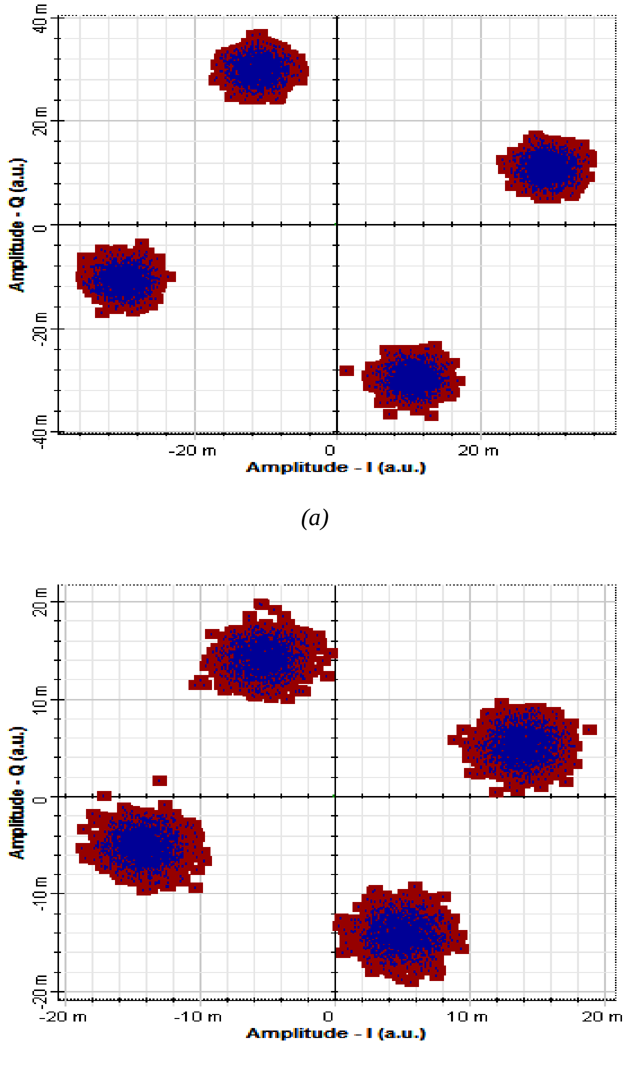


(b)

Fig. 4. Measured Total optical power for (a) Channel 1 (b) Channel 2 (color online)

From the results presented in Fig. 3 and 4 it can be observed that for channel 1 with HG01 mode, the SNR is computed as 30.82 dB, 19.47 dB, and 5.77 dB and for channel 2 with HG03 mode the SNR is computed as 30.22 dB, 18.25 dB, and 1.57 dB at a link range of 1000 m, 1500 m, and 2000 m respectively using a single beam transmission, whereas by using 4-beams, the SNR for channel 1 is computed as 42.84 dB, 31.89 dB, and 21.42 dB and for channel 2 is computed as 42.17 dB, 31.24 dB, and 20.41 dB at a link range of 1000 m, 1500 m, and 2000 m respectively. Similarly the total received optical power for channel 1 using single beam is reported as -22.15 dBm, -44.26 dBm, and -64.52 dBm and for link using 4-beams is reported as 1.92 dBm, -20.12 dBm, and -40.59 dBm at a link range of 1000 m, 1500 m, and 2000 m respectively whereas for channel 2 using single beam, total received optical power is reported as -28.61 dBm, -39.91 dBm, -70.59 dBm and for link using 4-beams total optical received power is reported as -4.53 dBm, -15.82 dBm, and

-47.05 dBm at a link range of 1000 m, 1500 m, and 2000 m respectively. From the numerical results, an 18 dB improvement in SNR and 22 dB in received power is observed by using 4-beams transmission in comparison to a single beam. The results presented show that maximum link range under heavy fog conditions with acceptable performance (SNR~ 20 dB) using a single beam is 1500 m which increases to over 2000 m using the proposed 4-beams transmission system. The measured clear constellation diagrams of the received signal for different channels at 2000 m as shown in Fig. 5 demonstrate a successful transmission of 40Gbit/s-80GHz data by using 4-beams.

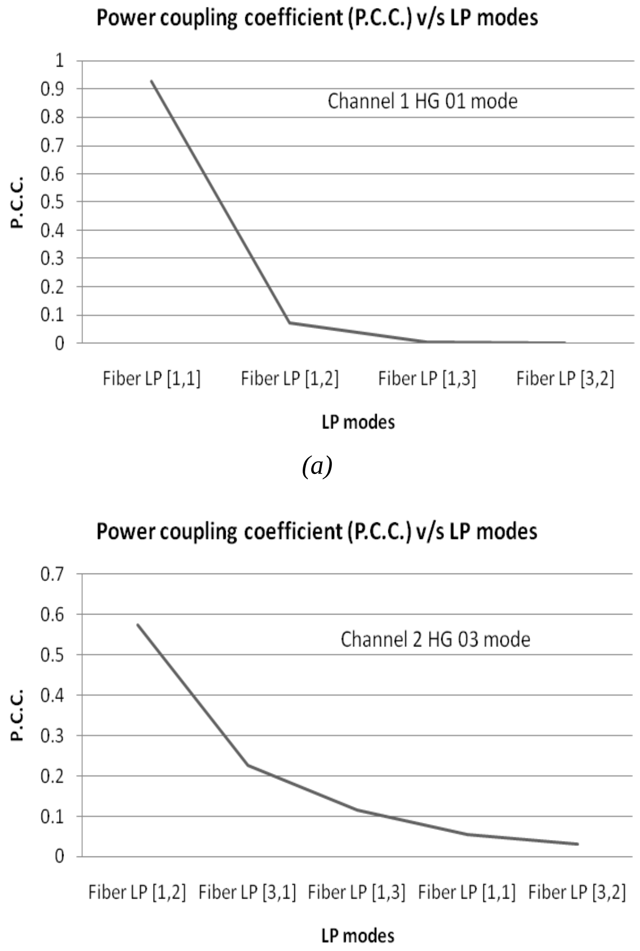


(a)

(b)

Fig. 5. Constellation plots for (a) Channel 1 (b) Channel 2 at 2000 m using 4-beams (color online)

Also, from the results presented in Fig. 3 and 4, it can be observed that channel 1 HG01 mode performs better as compared to channel 2 HG03 mode. This is because HG01 mode is more robust to multipath fading and atmospheric turbulence as compared to HG03 mode. Fig. 6 shows the decomposition power coupling coefficient (P.C.C.) analysis of different channels at the receiver terminal as a function of fiber LP modes at 2000 m. From the results presented in Fig. 6, it can be observed that for HG01 mode, 92.67% of the total power is transferred to LP11 mode whereas rest of the power is transferred to LP12, LP13, and LP32. Similarly for HG03 mode, 57.25% of the total power is transferred to LP12 mode whereas rest of the power is transferred to LP31, LP13, LP11, and LP32 mode. The results show that more intermodal power coupling occurs for HG03 mode as compared to HG01 mode which authenticates the link performance as reported in Fig. 3 and 4.



(a)

(b)

Fig. 6. Modal decomposition for (a) channel 1 HG01 mode (b) channel 2 HG03 mode

In order to further improve the performance of the proposed link under heavy fog, we have reported an enhanced detection in which a Square root module (SRm) is deployed after the PIN at the receiver. The scattering of the optical signal due to different atmospheric conditions such as heavy fog results in temporal dispersion of the information signal transmitted due to multiple propagation paths thus leading to inter-symbol interference (ISI). The quadratic transfer function of the PIN photodiode used at the receiver terminal converts this linear distortion into a non-linear distortion and degrades the quality of the received signal. Here, in order to mitigate the non-linear response of PIN, we have incorporated an SRm device at the receiver. The improved performance of the RoFSO link using 4-beams in terms of SNR and total optical power by deploying the proposed SRm at the receiver unit is shown in Fig. 7. From the results presented, there can be observed an significant performance enhancement by deploying SRm at the receiver. From the results, it can be seen that the maximum achievable link range with acceptable performance (SNR~20 dB) increases from 2000 m to 4000 m by using SRm. For better clarity, we demonstrate constellation diagram and RF spectrum of the received signal with and without SRm at different link range in our proposed link in Fig. 8 and 9 respectively.

The performance comparison of the proposed hybrid MDM-OFDM-Multibeam based RoFSO transmission link incorporating enhanced detection with previously reported works has been shown in Table 1. The comparative analysis in Table 1 shows that the proposed system has a better figure of merit (information capacity × link distance) as compared to the existing works.

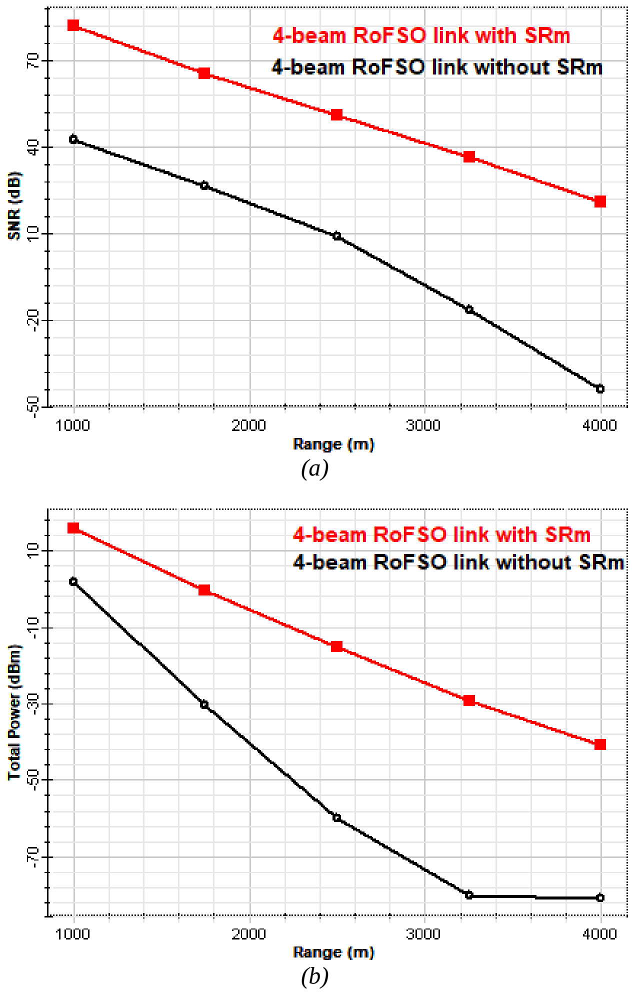


Fig. 7. Evaluation of (a) SNR (b) Total received power v/s link range with and without SRm at the receiver terminal (color online)

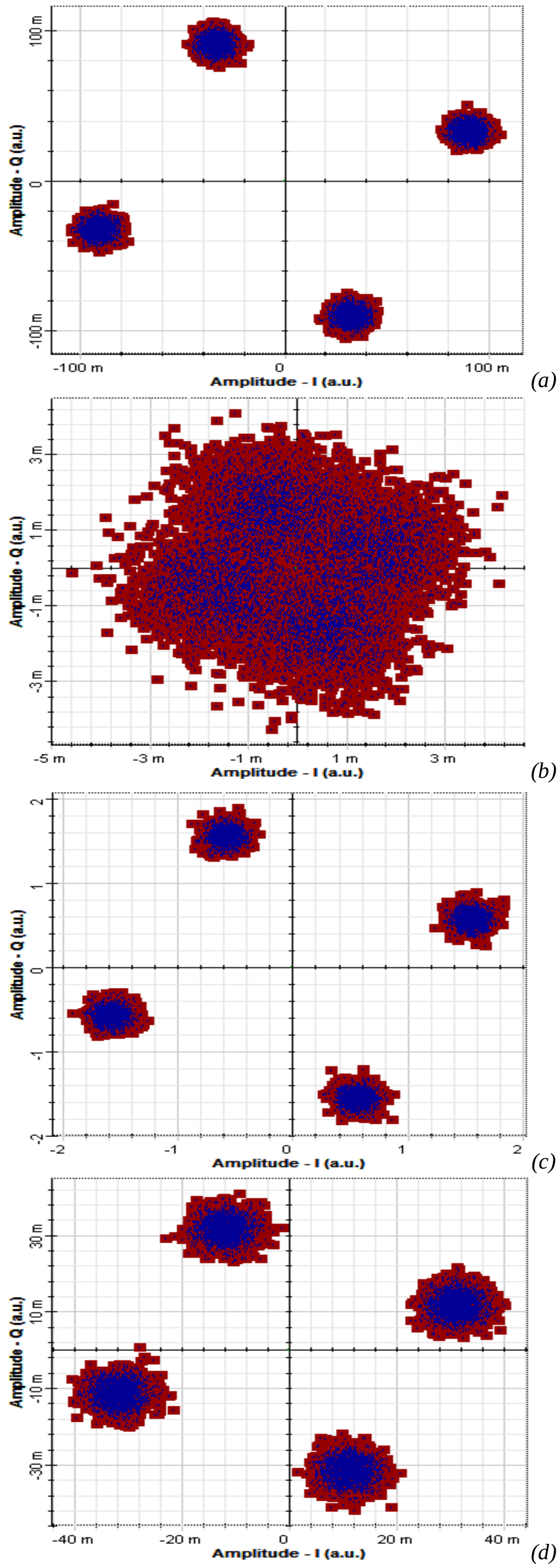


Fig. 8. Measured constellation diagram (a) at 1500m link range without using SRm (b) at 4000m link range without using SRm (c) at 1500 m link range using SRm (d) at 4000m link range using SRm (color online)

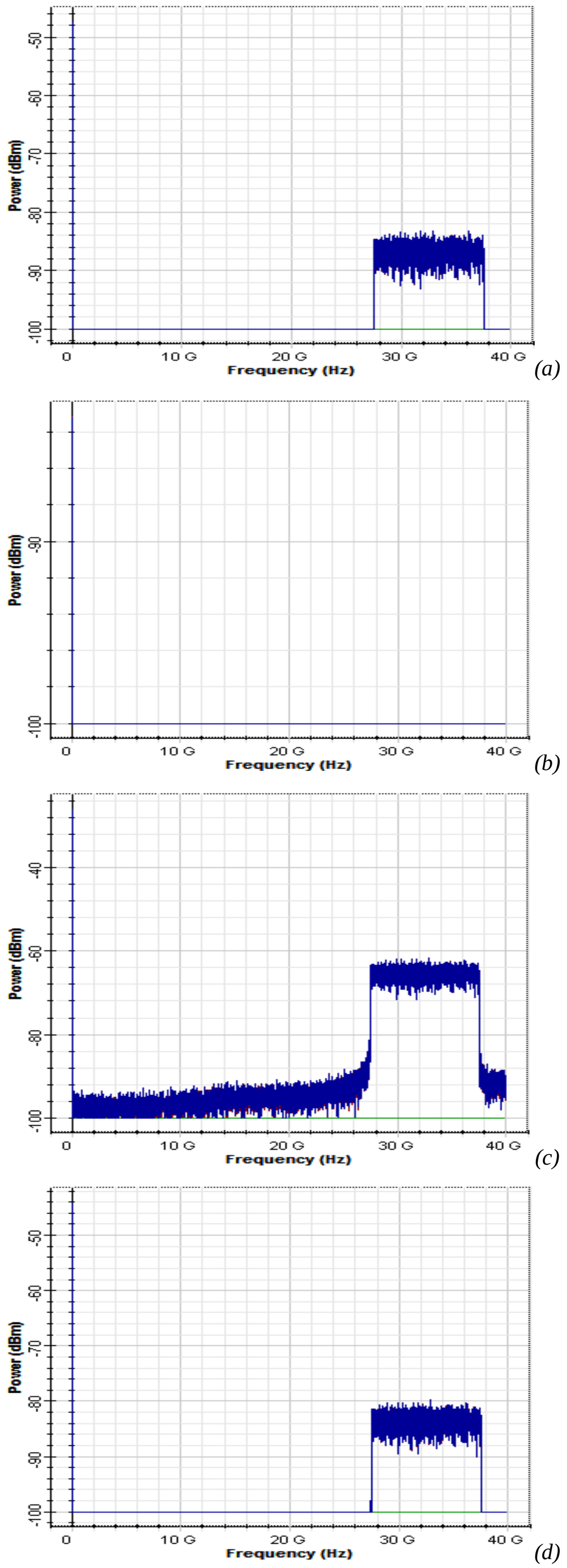


Fig. 9. Measured RF spectrum (a) at 1500 m link range without using SRm (b) at 4000 m link range without using SRm (c) at 1500 m link range using SRm (d) at 4000 m link range using SRm (color online)

Table 1. Comparison of the proposed RoFSO link with existing works

Ref	Method/Technique	Atmospheric condition	Data rate	Link Range
Ref [10]	DWDM based RoFSO link	Heavy Fog	$12\lambda \times 2.5$ Gbit/s	2000 m
Ref [13]	OFDM based RoFSO link	Heavy Fog	10 Gbit/s	2500 m
Ref [25]	NRZ encoded MDM based RoFSO link using spiral phased HG modes	Heavy Fog	2×2.5 Gbit/s	1100 m
Ref [26]	NRZ encoded MDM based RoFSO link with PCF mode selector	Heavy Fog	3 ×2.5 Gbit/s	200 m
Ref [27]	NRZ encoded MDM based RoFSO link with solid core PCF mode selector	Heavy Fog	2×2.5 Gbit/s	200 m
Ref [28]	NRZ-DPSK encoded MDM based RoFSO link	Heavy Fog	2×20 Gbit/s	1300 m
Ref [29]	AMI encoded MDM based RoFSO link	Heavy Fog	2×5 Gbit/s	1600 m
In this work (Proposed system)	Hybrid MDM-OFDM-Multibeam based RoFSO link with enhanced detection	Heavy Fog	2×20 Gbit/s	4000 m

4. Conclusion

In this work, we investigate the performance comparison of a single beam and the proposed 4-beams in OFDM-MDM based RoFSO link. Two 20Gbit/s-40GHz independent signals were successfully transmitted over an FSO link range of 2000 m using the proposed link. From the numerical results, an 18 dB improvement in SNR and 22 dB in received power is observed in the proposed RoFSO link by using 4-beams transmission in comparison to a single beam. Also, an enhanced performance of the proposed link by using an SRm at the receiver terminal is reported. The results presented show that the proposed link prolongs to over 4000 m with acceptable performance under heavy fog conditions by using the proposed hybrid OFDM-MDM-Multibeam based RoFSO transmission link. In future works, the proposed system can practically be realized by performing experiments.

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