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High Speed MDM-Ro-FSO System by Incorporating Spiral Phased Hermite Gaussian Modes

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Abstract: *In the wake of growing challenges of dispersing communication services in rural areas, Radio over Free Space (Ro-FSO) is a useful technology that can carry heterogeneous services. This work focuses on transmitting two independent channels, each carrying 2.5Gbps data and 10GHz radio signal, by utilizing mode division multiplexing (MDM) of two spiral phased Hermite Gaussian modes (HG00 and HG01) free space optical (FSO) link. It also evaluates the performance of the proposed Ro-FSO system under the impact of beam divergence and various atmospheric turbulences such as moderate fog and heavy fog.*

Keywords: Mode Division Multiplexing, Free Space Optics, Radio over free space, Hermite Gaussian Modes

I Introduction

With the higher requirement of information accessibility irrespective of time, place and situation, the demand of communication has also increased. The availability of communication services is fast becoming an indispensable part of our daily life. For instance, the use of tablets is assumed to generate 50% mobile data traffic in 2020 which is 7.6 times higher than in 2015 [1]. This has further resulted in the relevance of a universal network connected through heterogeneous devices for catering to the demand without bothering the issue of geographical locations. Current wireless network systems involve independent operators setting up and managing their own radio resources and networks autonomously, which is highly expensive and involves delayed installation of new wireless services particularly in rural and remote areas [2-4]. Among wireless access networks, Radio over Fibre (RoF) technology has proved to be a common platform for radio signal transmission using optical fibres without changing radio format [5-9]. This technology offers cost-effective and simplified radio access network while supporting high-speed multimedia to achieve the increasing demand in case of limited radio spectrum. Optical fibre features high capability and low transmission loss which can enhance transmission capacity and distance of wireless communication [10]. However, this solution can be applicable only when fibre cable infrastructure is available with reasonable installation cost. Moreover, the availability of independent wireless network operators leads to redundant equipment and investment on infrastructures. This further prevents the new wireless service from launching while stopping the employment of micro- and pico-cellular architecture for upgraded radio frequency efficacy. These complications are likely, especially in urban buildings, underground and rural areas where broadband fibre-infrastructures are difficult to construct due to their low population and high cost [11]. In this case, radio over free space (Ro-FSO) technology – a combination of free space and radio over fibre scheme – can be useful for transporting radio carrier over free space link. Ro-FSO can be utilised by existing mobile cellular architectures in rural areas to a) distribute RF signals at high bandwidth, b) have low attenuation losses, and c) consume low power [12-14].

Recent improvements in Ro-FSO include experimental measurements [15-17] and statistical modelling [18-20] under various atmospheric turbulence and scintillation effects. The capacity of Ro-FSO systems can be enhanced by exploiting multiplexing in wavelength [21], intensity [22] and phase dimensions [23]. To transmit multiplexing data stream, eigen mode dimension is relatively untapped in Ro-FSO systems through a single channel, especially in the case of MDM. Spatial light modulators [24], optical signal processing [25, 26], few mode fibre [27, 28], photonic crystal fibres and modal decomposition methods [29] are used to implement MDM in optical fibre communication.

In 2012 [30], 2 Tbps data are transported over 1m FSO link by incorporating MDM of 2 orbital angular momentum (OAM) modes (*l=8, l=16*) and wavelength division multiplexing (WDM). The OAM modes are generated by using two spatial laser modulators (SLMs) (512 X 512 pixels). In 2013 [31], 40 Gbps QPSK signal is transmitted over 1m FSO link by MDM of 3 OAM modes (l=1, l=3 and l=5) under atmospheric turbulences. The OAM mode is excited by two reflective SLMs. In 2014 [32], high speed transmission of 100 Tbps data is reported over 1m FSO link by combining MDM, WDM and polarization division multiplexing (PDM) techniques. 10 OAM modes (*l=+4, +7, +10, +13, +19, -4, -7, -10, -13, -19*) are excited by liquid crystal-based reflective SLMs on X and Y polarization. In another study [33], 3 km FSO link is established in Vienna to transmit grey scale images by using MDM of 4 OAM modes (*l= 1, 1 rotated, 4 and 15*).

In 2016 [34], 400 Gbps data are transmitted over 120m FSO link by using 4 OAM beams $l = \pm 1$ and $l = \pm 3$. In another work [35], two OAM beams $l = \pm 3$ are used to transmit 40Gbps 16 QAM data over 260m FSO link. Recently in 2017 [36], 100 Gbps data is transmitted over span of 8 km by employing MDM and optical code division multiplexing (OCDMA) scheme. Although MDM is demonstrated for few Ro-FSO works [37-42], it largely remains an unexploited area. The current paper aims to examine the Ro-FSO technology under atmospheric turbulences while combining modes for FSO-MDM by adopting two spiral-phased HG modes using vortex lenses, which is not reported in any previous work to the best of authors' knowledge. The rest of the paper includes system description in Section 2, results and discussion in Section 3 followed by conclusion in Section 4.

2 System Description

The diagram in Fig.1 features spiral-phased HG modes of the proposed FSO model designed in OptiSystem^{TM} software.

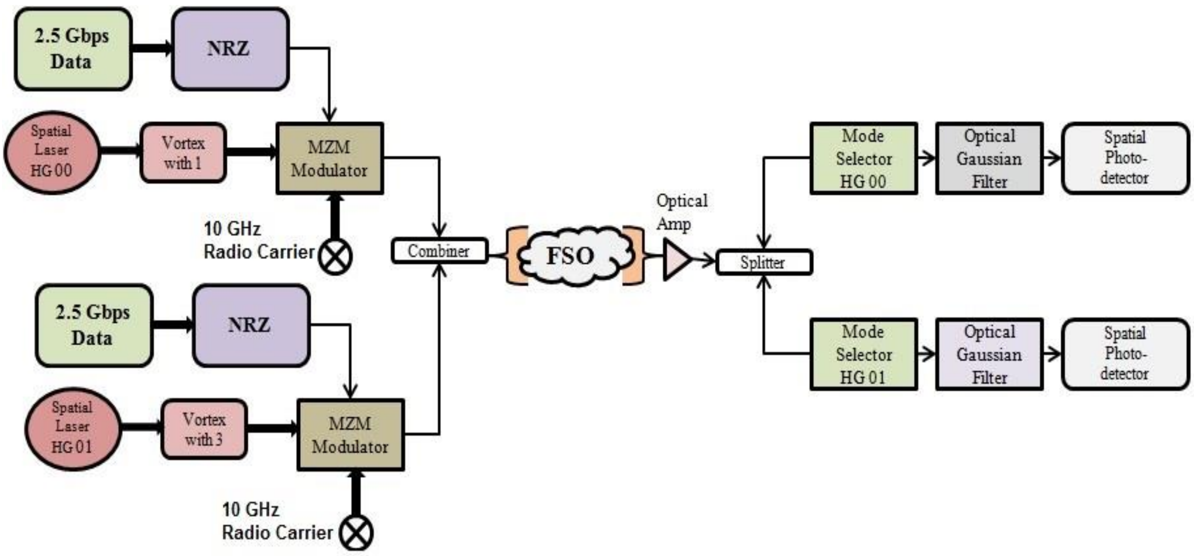


Fig.1 Proposed 2.5Gbps-10GHz System

The proposed architecture features two independent non-return-to-zero (NRZ) encoded channels, each carrying 2.5 Gbps data stream and 10 GHz radio signal over 850 nm optical spatial carrier with the power of 10 dB. For data transmission, two laser modes of spot size 5 µm – HG 00 with vortex *m=1* for Channel 1 and HG 01 with vortex *m=3* for Channel 2 – are used. description for HG mode is given as [43]:

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

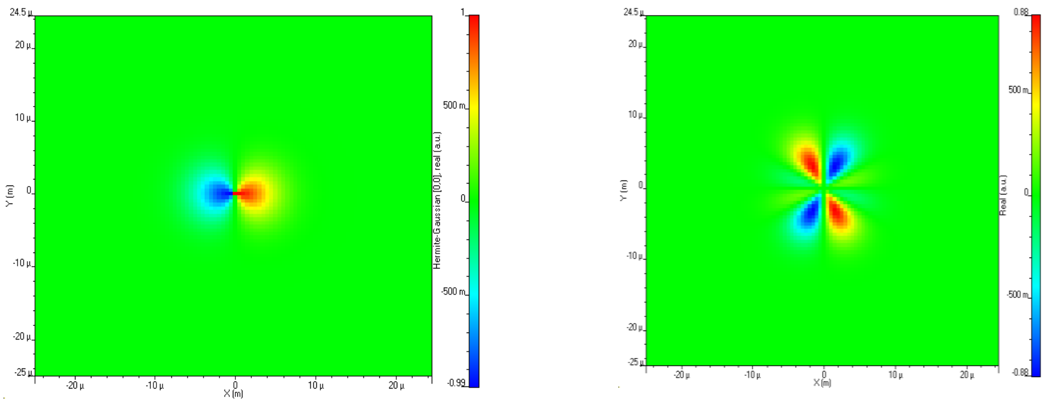
In the above equation, *m* and *n* are mode dependencies on the *x*- and *y*-axes, *R* is the curvature radius, W_o is the spot size; and H_m and H_n are the Hermite polynomials. As shown in Fig.1, the required phase to HG modes is generated by using vortex lens. The applied phase is explained mathematically as [44]:

$$T(x,y) = \exp[-\frac{\pi n(x^2+y^2)}{2\lambda f} + ma\tan(\frac{x}{y})] \quad (2)$$

In the above equation, *f* is the focal length, *m* is the vortex parameter, *n* is the refractive index and *a* is the arbitrary complex number. Fig. 2(a) and (b) show the phase of excited modes generated with vortex lens. Free-space distance ranging from 8 km to 15 km is used for combining, amplifying and transmitting the outputs of the two channels. Free-space optics is mathematically described as [45]:

$$P_{Received} = P_{Transmitted}\left(\frac{d_R{}^2 R}{(d_T+\theta R)^2}\right)10^{-\alpha R/2} \quad (3)$$

In the above equation, d_R^2 is the receiver aperture diameter, d_T is the transmitter aperture diameter, Θ is the beam divergence, *R* is the range, and α is the atmospheric attenuation. The attenuation for clear weather is considered as 0.14 dB/km whereas under atmospheric turbulences, it is considered as 16 dB/km for moderate fog and 22 dB/km for heavy fog [46, 47]. The transmission channel uses pre- and post-compensation techniques via optical amplifier of 14 dB. At the receiver's side, extraction of the transmitted mode occurs through non-interferometric modal decomposition [48]. This output mode is then received by a spatial PIN detector which is further received by low-pass Gaussian filter to retrieve the original baseband signal. Fig. 2 shows excited modes using vortex lens and spatial continuous wave laser.



(a) (b)

Fig.2 Excited Modes (a) HG 00 with vortex *m=1* (b) HG 01 with vortex *m=3*

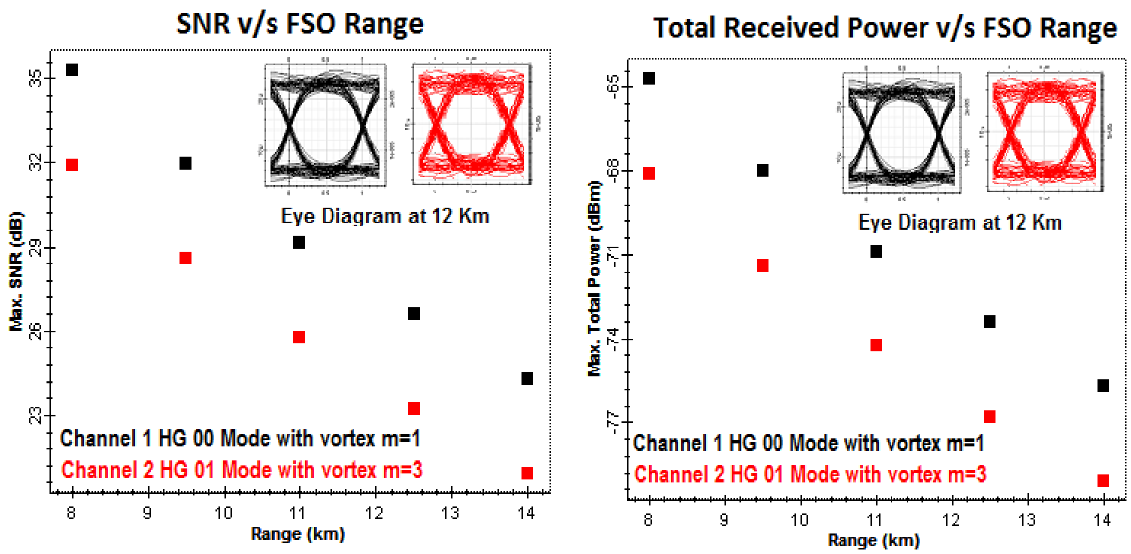
Parameters	**Values**
Input Power	10 dBm
No of Stages Optical Amplifier Used for Compensating signal	2 (Before and after FSO Channel)
Responsivity of PIN Photo-detector	1 A/W
Thermal Power Noise Density of PIN Photo-Detector	100e-024 w/Hz
Dark Current of Photo Diode	10 nA

Table 1: Simulation parameters

The other parameters of proposed system are presented in table 1.

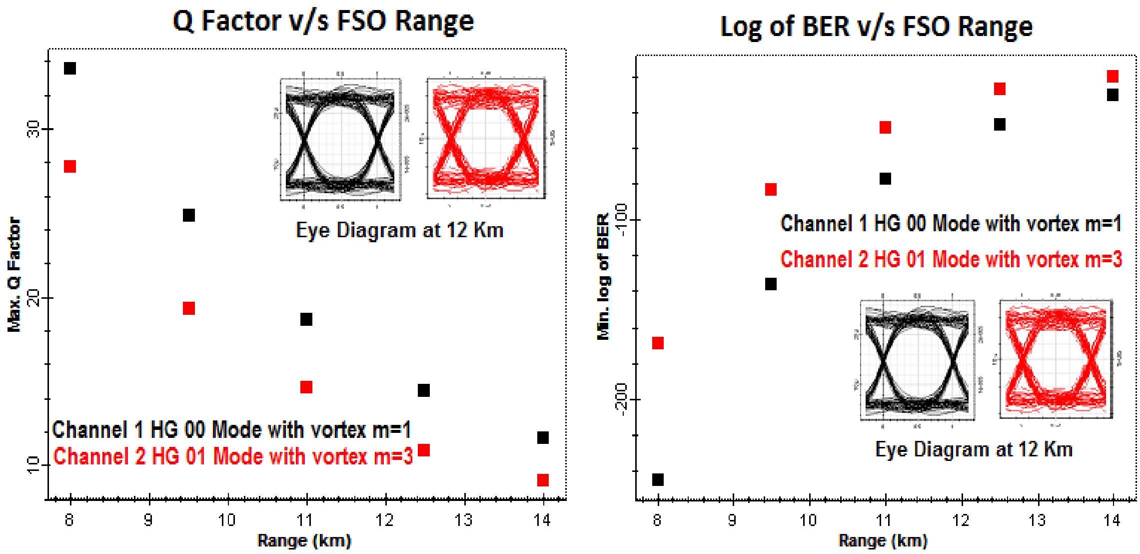
3 Results and Discussion

The results from the proposed Ro-FSO-MDM transmission system show the SNR and total received power for LG modes as shown in Fig.3. It has been observed that HG 00 with vortex *m=1* (channel 1) performs better than HG 01 with vortex *m=3* (channel 2) as the latter is more affected to multipath fading. The values of SNR are noticed as 35.11 dB, 29.14 dB and 24.11 dB for Channel 1 and 31.11 dB, 25.34 dB and 20.54 dB for Channel 2 with the FSO range of 8 km, 11 km and 14 km. Similarly, the value of power is noticed as -64.11 dBm, -70.43 dBm and -75.43 dBm for Channel 1 and -68.11 dBm, -74.23 dBm and -79.23 dBm for channel 2 with the FSO range of 8 km, 11 km and 14 km.



(a) **(b)**

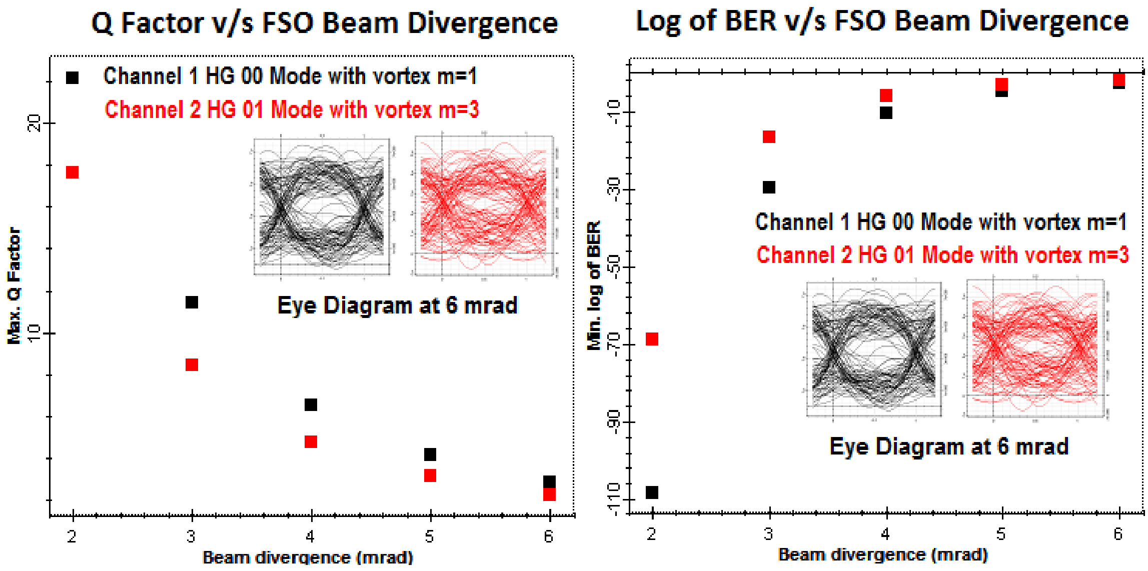
Fig.3 Evaluation of SNR and Total Received Power (a) SNR v/s FSO Range (b) Total Received Power v/s FSO Range



(a) **(b)**

Fig.4 Evaluation of Q factor and Log of BER (a) Channel 1 (b) Channel 2

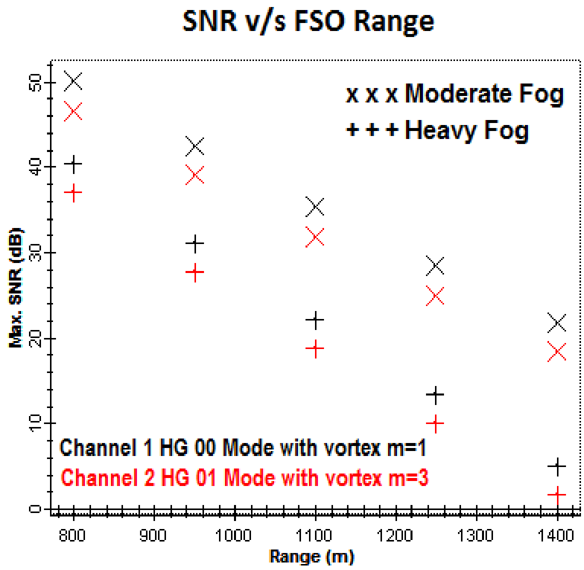
As shown in Fig.4 (a), the values of Q factor are noticed as 33.11 dB, 18.23 dB and 11.57 dB for Channel 1 and 27.23 dB, 14.34 dB and 9.33 dB for Channel 2 with the FSO range of 8 km, 11 km and 14 km. Fig.4 (b) shows the values of log of bit error rate as -245.811, -77.222 and -30.584 for Channel 1 and -169.275, -48.163 and -19.504 for Channel 2 with the FSO range of 8 km, 11 km and 14 km. The clear eye diagrams measured at 12 km as shown in Fig.3 and Fig.4 show that 2.5Gbps-10GHz data is transmitted successfully with acceptable SNR, Q Factor, BER and total received power. Fig.5 shows the performance of the proposed Ro-FSO system under the impact of divergence of beam travelling through FSO channel as it plays important role in designing FSO transmission systems. As shown in Fig.5 (a), the values of Q factor are noticed as 22.11 dB, 6.14 dB and 2.82 dB for Channel 1 and 17.11 dB, 4.11 dB and 2.12 dB for Channel 2 with the beam divergence of 2 *mrad*, 4 *mrad* and 6 *mrad* at 12 km FSO link.



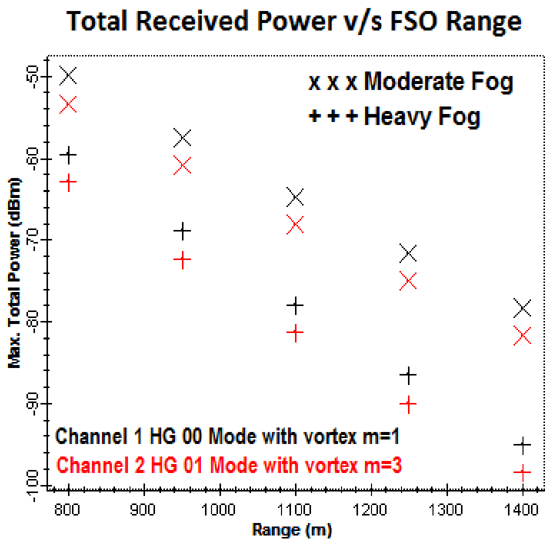
(a) (b)

Fig.5 Evaluation of Q Factor and Log of BER against FSO Beam Divergence (a) Q Factor (b) Log of BER

Fig.5 (b) shows the values of log of BER computed as -108.495, -10.515 and -2.685 for Channel 1 and -70.015, -6.146 and -1.892 for Channel 2 with the beam divergence of 2 *mrad*, 4 *mrad* and 6 *mrad* at 12 km FSO link. The distorted eye diagrams at FSO beam divergence of 6 *mrad* show that the proposed system can handle beam divergence only up to 4mrad with acceptable Q factor and BER. As divergence increases from 4 *mrad*, distortion in eye also increases. Moreover, evaluation of the performance of the proposed Ro-FSO system under the impact of various atmospheric turbulences shows its results. In case of moderate fog, the values of SNR are computed as 50.11 dB, 35.54 dB and 21.23 dB for Channel 1 and 46.24 dB, 31.94 dB and 18.34 dB for Channel 2 with the FSO range of 800 m, 1100 m and 1400 m as shown in Fig.6(a).



(a)



(b)

Fig.6 Evaluation of SNR and Total Received Power against FSO Range under atmospheric turbulences (a) SNR (b) Total Received Power

In case of heavy fog, the values of SNR are computed as 40.11 dB, 22.15 dB and 4.11 dB for Channel 1 and 37.13 dB, 18.22 dB and 1.04 dB for Channel 2 with the FSO range of 800 m, 1100 m and 1400 m. Similarly, in case of moderate fog, the values of total received power are computed as -49.95 dBm, -64.67 dBm and -78.11 dBm for Channel 1 and -53.11 dBm, -68.05 dBm and -81 dBm for Channel 2 with the FSO range of 800 m, 1100 m and 1400 m as shown in Fig. 6(b). In case of heavy fog, the values of total received power are computed as -59.11 dBm, -78.11 dBm and -96.23 dBm for Channel 1 and -62.32 dBm, -81.65 dBm and -98.13 dBm for Channel 2 with the FSO range of 800 m, 1100 m and 1400 m. This clearly shows the successful transmission of 2x2.5Gbps-10GHz data under moderate fog up to 1400 m whereas FSO link prolongs only up to 1100 m under heavy fog with acceptable SNR and total received power.

4 Conclusion

This work has transmitted 2 x 2.5Gbps data-10GHz radio signal over FSO link. To do so, it used mode division multiplexing scheme of two independent channels through spiral-phased HG 00 mode with vortex lens *m=1* and HG 01 mode with vortex lens *m=3*. Simulations proved that FSO link prolongs to 14 km with acceptable SNR (for channel 1= 24.11 and for channel 2= 20.54 dB) and log of BER (for channel 1= -30.584 and for channel 2 = -19.504) under clear weather conditions. Whereas in case of various atmospheric turbulences, FSO link prolongs to 1400 m in moderate fog with acceptable SNR (for channel 1=21.23 dB and for channel 2= 18.34 dB). In case of heavy fog, FSO link prolongs to 1100 m with acceptable SNR (for channel 1=22.15 dB and for channel 2= 18.22 dB).

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Brief Profile

Dr. Sushank Chaudhary has completed his PhD at Optical Computing and Technology Laboratory, UUM, Malaysia. He has published more than 30 research papers in reputed international journals and conferences. During his PhD tenure, he was invited by Government College Engineering Ajmer, I.I,T Bhubaneshwar, NIT Bhopal, SMVDU Jammu, SVNIT Surat and BHEL Hyderabad as a guest speaker to deliver a lecture on advanced optical communication systems and training of Optiwave software. Hailed from Himachal Pradesh, India, he was a senior research associate at Optiwave before joining PhD. During his job, he was invited by more than 50 universities to give training on Optiwave software – OptiSystem, OptiFiber, OptiBPM, OptiGrating, OptiFDTD and OptiSpice software. He was also invited by various research organizations such as ISRO Ahmedabad, NSTL-DRDO Vishakhapatnam. He also received award of Born Navigator for his research paper from DRDO Hyderabad. He has obtained M.Tech in Electronics and Communication Engineering with specialization of optics communication from Govt college of Punjab, Ferozepur in 2012; B.Tech in Electronics and Communication Engineering from Govt. college of Punjab, Lehragaga in 2010 and Diploma in Electronics and Communication engineering from Govt. Polytechnic College, Rohroo in 2007. His main research interests are: Free Space Optics, Radio over Free Space Optics, Radio over Fiber, Integrated Optics, Multimode Transmissions, Hybrid Optical and Wireless Communication systems, Ultra dense wavelength division multiplexing, Inter-Satellite Communication Systems, Opto-Electronical Transmission systems and Advance Optical communication systems.

Assoc. Prof. Dr. Angela Amphawan received her PhD in optical communications engineering from University of Oxford, United Kingdom. She is currently Head of the Optical Computing and Technology Research Laboratory at School of Computing, Universiti Utara Malaysia and a Fulbright Research Fellow at Massachusetts Institute of Technology, USA. Due to her excellent standing in the optics community, she has been appointed to serve on the IEEE Nanotechnology Council and IEEE Sensors Council. She has won the Fulbright Award and the International Academic Award by the Deputy Prime Minister for her outstanding contribution. Her research has been funded by the Fulbright Foundation, Telekom Malaysia, German Academic Exchange and the Malaysian Ministry of Higher Education. She has been invited as a keynote speaker for the Fulbright-Malaysian Communications & Multimedia Commission Seminar (MCMC) Academic-Industrial Seminar, IEEE International Conference on Microwave and Photonics, International Conference on Communication and Computer Engineering and several others conferences. She has won two Best Paper Awards and several exhibition medals. She currently serves on the Editorial Board of International Journal of Electrical and Computer Engineering, International Journal of Informatics and Communication Technology, International Journal of Emerging Technology and Advanced Engineering, Applied Physics and Mathematics. She has also served as Publicity Co-chair for the IEEE Wireless Communications and Networking Conference International Conference (WCNC), Technical Committee for Electrical Engineering, Computer Science and Informatics, International Conference on Internet Applications, Protocols and Services and several other conferences.