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To Propose High Speed (4×24 Gbps) Dense Wavelength Division (DWDM) and MDM 64-QAM-OFDM Ro-FSO System

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A B S T R A C T

Millimetre (mm) waves with frequencies ranging from 30 to 300 GHz have emerged as a potential carrier for high-speed fifth-generation services. However, one of the primary issues for internet service providers is the low capacity of millimetre waves. By combining the wireless system with optical communication technologies, radio over free space (Ro-FSO) might be a viable option for transporting high-speed millimetre waves. In this work, a high speed (4×24 Gbps) 64-QAM-OFDM Ro-FSO link which can support the transmission of 4 independent high speed channels over 35 km, each one carrying 24 Gbps data up-converted to 40 GHz mm wave is designed. The spectral efficiency of proposed Ro-FSO link is improved by incorporating mode division multiplexing (MDM) of linear polarized (LP) mode 01 and 02 and dense wavelength division multiplexing (DWDM) scheme with the channel spacing of 0.4 nm (50 GHz).

Keywords: QAM, OFDM, Ro-FSO, LP, MDM

1. Introduction

Over the last decade, advancements in communication technology have made it possible for IoT (internet of things) to make day-to-day activities such as transportation, appliances, food shopping, and health care more convenient [1]. IoT has enabled remote access, making it a necessary measure in today's environment. It is desirable to develop 5G technology to allow the IoT on such a big scale and to support so many services. 5G technology has been determined to be the best method for providing last mile connection in rural areas or underdeveloped terrains [2]. The researchers were able to increase the current capacity of Optical Wireless Communication by combining millimetre waves (mm waves) with a free space optics (FSO) technology [3]. Applications that consume a lot of bandwidth, such as video on demand, conferencing, high-speed online gaming, live streaming, and smart appliances, are driving up the need for high channel bandwidth, as well as the number of end users [4]. As a result, in order to create a large number of access points for wireless local area networks (WLAN), strict frequency scheduling is required, according to IEEE 802.11 a/b/e/g/n specifications. Co-Channel interference, which is exacerbated by increased power levels necessary to serve large end users, can negatively impact WLAN implementation by affecting operational scheduling, frequency intuiting, and service quality (QoS) [5]. A possible difficulty for every network builder is spectrum deficiency in the RF spectrum and resource planning of available spectrum. The use of mm-wave FSO systems, also known as Radio over Free Space Optics (Ro-FSO) technology, might be a viable solution to the concerns listed above [6]. Ro-FSO technology uses an unregulated and underutilised portion of the electromagnetic spectrum as an optical carrier for RF communications travelling across free space. Ro-FSO has a number of advantages over WLANs, including an abundance of unlicensed spectrum, high speed, huge bandwidth, immunity to electromagnetic interference, quieter and quicker connections, and improved data security [7]. Because all of the necessary expensive equipment for signal conditioning such as multiplexing and demultiplexing, signal encoding and encoding, switching, hand-off, and frequency up–down conversion is pooled with the central base station, Ro-FSO allows for a cost-effective implementation without the use of expensive optical fibres and WLAN equipment [8]. Despite its benefits, Ro-FSO operations are restricted by external factors such as air attenuation, scintillation, multipath fading, scattering, line of sight hindrances, signal absorption, and so on, all of which reduce the quality of the sent signal. Rain, snow, haze, and fog cause a lot of turbulence in the atmosphere [9]. In tropical locations, fog is the most common source of signal loss, and it limits the maximum achievable communication distance in Ro-FSO transmission. Orthogonal frequency division multiplexing

(OFDM) may be used with the Ro-FSO system to achieve a high-speed system that is immune to co-channel and inter-symbol interference [10]. The information is carried by mutually orthogonal subcarriers in OFDM, which provides invulnerability. Researchers have also described devices that use polarisation to achieve maximum transmission capacity and high data speeds. Mode division multiplexing (MDM), on the other hand, is a well-known multiplexing strategy that uses [11] Eigen modes to extend data transmission range in optical multimode communication systems. MDM uses multimode fibre photonic crystal fibre, optical signal processing, and a spatial light modulator to provide simultaneous data transmission over a single wavelength across various spatial modes [12]. Although MDM is extensively utilised in multimode communication systems, researchers have been investigating the possibilities of using MDM with FSO systems in recent years [13].

Four separate channels, each containing 24 Gbps QAM-OFDM encoded data up-converted to 40 GHz millimetre wave, are sent over FSO connection by including MDM of two LP modes (01 and 02) and WDM of two wavelengths operating at 850 nm and 851 nm. The rest of the study is arranged as follows: Sect. 2 discuss the system setup of proposed system, Sect. 3 contains the obtained findings and their discussion, and Sect. 4 ends the paper.

2. System Setup

Figure 1 shows the schematic representation of proposed hybrid MDM-WDM-Ro-FSO system. Spatial laser with the power of 0 dBm and wavelength of 850 nm is used to excite two LP modes—LP 01 and LP 02. Internal structure of transmitter and receiver of first channel is shown in Figure 2 (a) and 2 (b). Each mode is used as carrier to transmit two independent channels (Transmitter 1 and Transmitter 2). Similarly another spatial laser with the power of 0 dBm and 850.5 nm is used to excite the two LP modes (LP 01 and LP 02) which is used as carrier to transmit another independent channels (Transmitter 3 and Transmitter 4). The output of all transmitters are combined and transmitted over FSO link with the span of 35 km.The atmospheric turbulences are assumed to be clear (0.1 dB/km) in the modelling of proposed MDM-WDM-Ro-FSO link. Semiconductor optical amplifier (SOA) with the injection current of 0.5 A is used as post equalization scheme to compensate the optical power loss through the channel. De-multiplexer is used to split the output of SOA into two required wavelengths (850 nm and 850 nm).For each wavelength, further splitter is used to split the output into the corresponding modes.

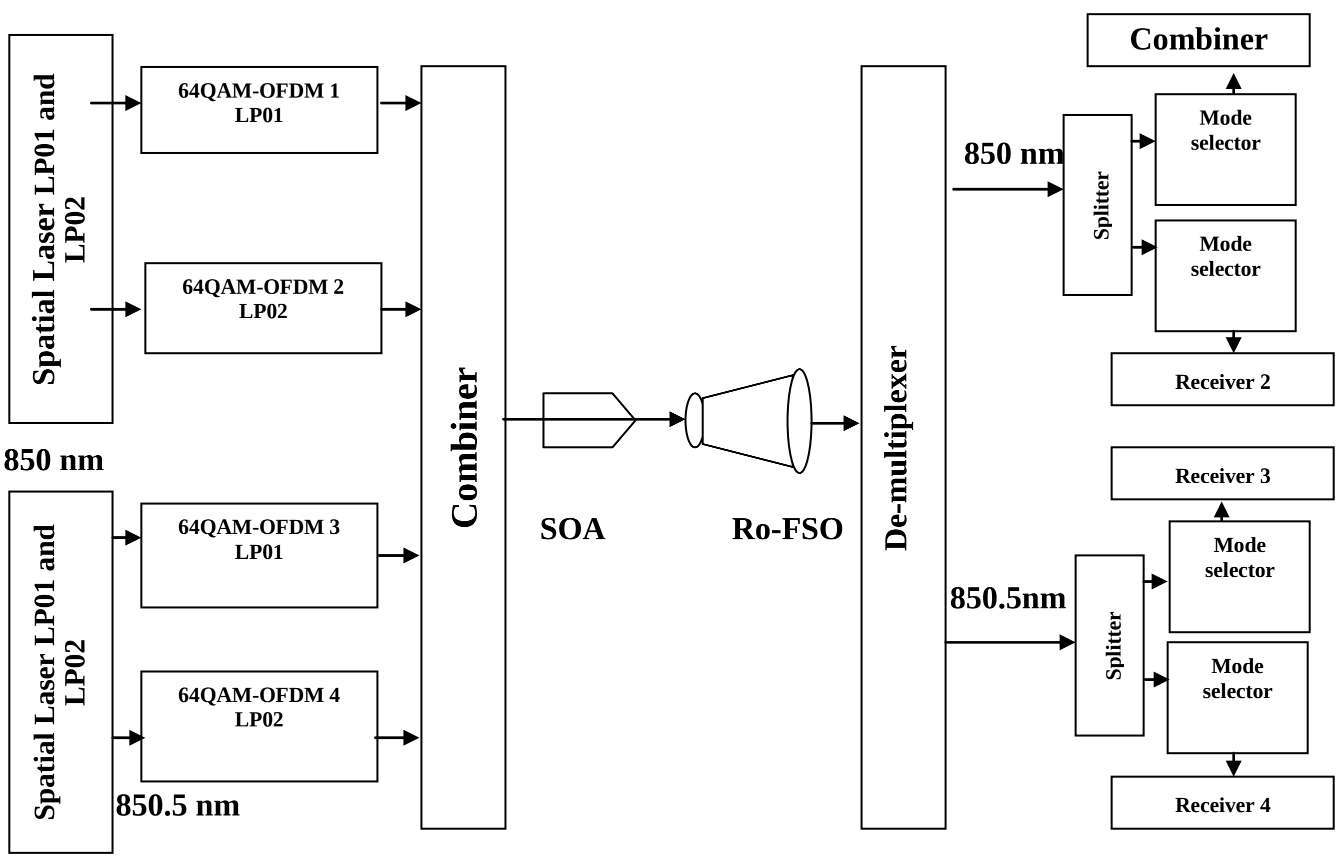


Fig. 1- WDM-MDM Ro-FSO system using 64-QAM-OFDM

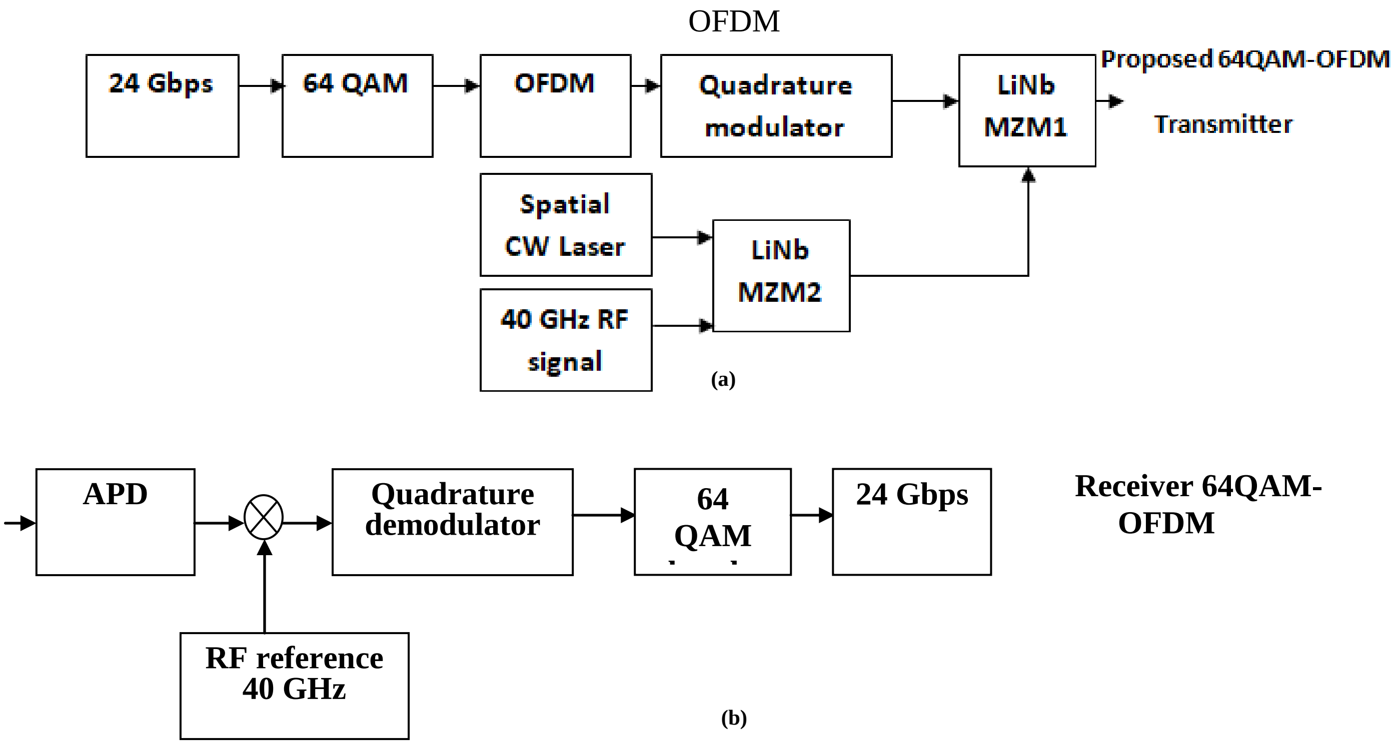
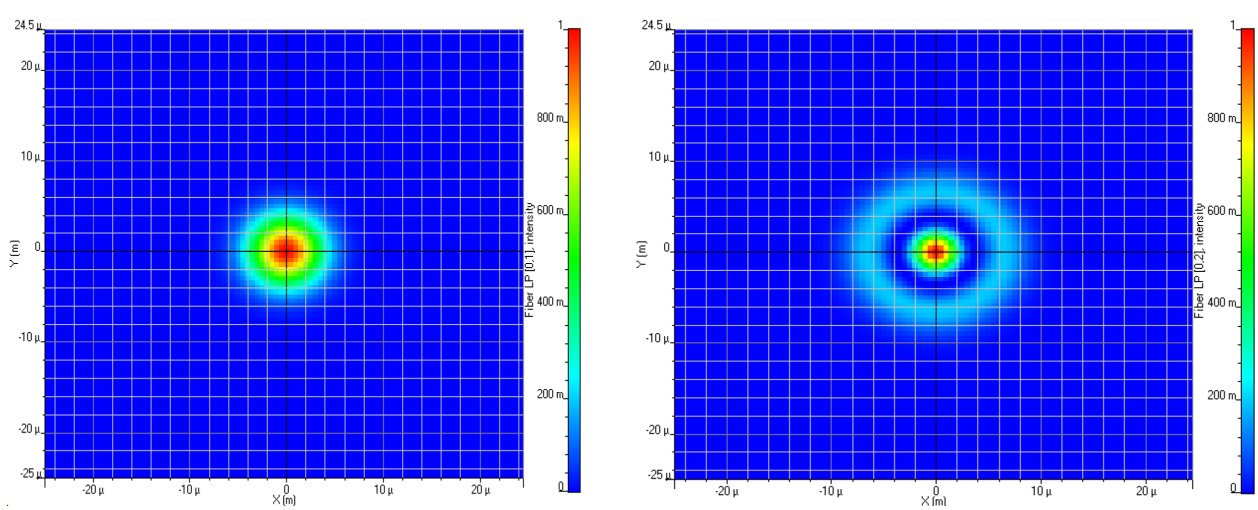


Fig. 2- Block diagram of proposed work (a) Transmitter (b) Receiver

In the transmitter section 24 Gbps data stream is encoded by using 64 QAM encoder. Further OFDM encoded data is further modulated at 7.5 GHz by using quadrature modulator (QM). This OFDM-QM modulated signal is then up-converted into 40 GHz mm signal, generated by sine generator, by using a mixer. This 40 GHz mm signal is modulated over optical carrier with the help of Lithium Niobate Mach-Zander Optical Modulator (LiNb-MZM). The optical carrier is generated by using spatial laser. Similarly, at the receiver side, Avalanche Photo Diode (APD) with the dark current of 0.9 A is used to capture the optical signal transmitted from transmitter through FSO link. The output of mixer is processed into demodulator followed by OFDM demodulator for the process of demodulation. Then finally 64 QAM decoder is used to construct the original 24 Gbps binary data.

3. Results and Discussions

Figure 3 (a) (b) represents the LP mode profiles such as LP01 and LP02 respectively that are used in the proposed work for realizing four channels from just two wavelengths i.e. 850 nm (LP 01 and LP 02), 850.5 nm (LP 01 and LP 02).



(a) **(b)**

Fig. 3- LP mode profiles representation of (a) LP01 (b) LP02

Figure 4 represents the measured Signal to Noise ratio (SNR) with respect to the link distance for channel 1, 2, 3, 4 which is transmitted over 850 nm and

850.5 nm wavelengths. The value of SNR decreases as the transmission distance of proposed Ro-FSO link increases. It indicates that channel 2, which uses LP mode 02 to transmit, is more impacted by fading introduced in the Ro-FSO link than channel 1, which uses LP mode 02 to transmit. At a distance of 10 km Ro-FSO connection, channel 2 suffers an 8 dB SNR loss compared to channel 1. However, at a Ro-FSO distance of 35 km, channel 1 and channel 2 have obtained an acceptable SNR of 20 dB. The SNR value of channel 4 falls to less than 20 dB beyond that distance. Similarly, there is a 7 dB SNR difference on channel 4 when transmitting in LP 02 mode against channel 3 while transmitting in LP 01 mode. At a Ro-FSO distance of 35 kilometres, Channels 3 and 4 attained an acceptable SNR of 20 dB. In terms of SNR at various distances, the performance of 850 nm utilising LP01 mode is the best.

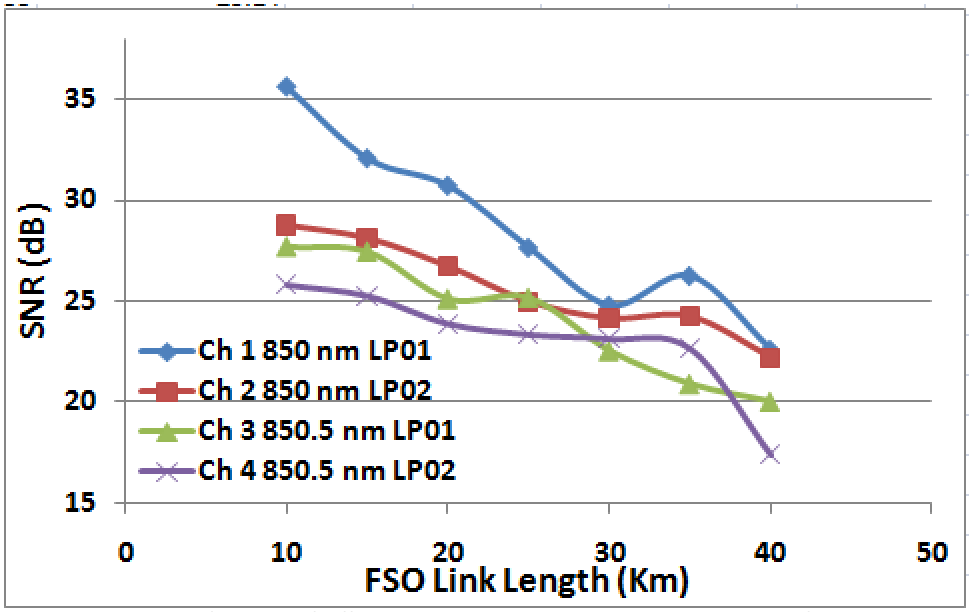


Fig. 4- Performance of different channels at varied FSO distances in terms of SNR

The measured power received for channel 1, channel 2, channel 3, and channel 4 is shown in Figure 5. From At a Ro-FSO link distance of 10 km, it reveals that channel 2 and channel 4 lose about 7 dBm power when compared to channel 1 and channel 3. This demonstrates that higher orders of mode LP 02 are more impacted than lower orders of mode LP 01. Table 1 displays the calculated SNR and received power for each channel as a function of distance.

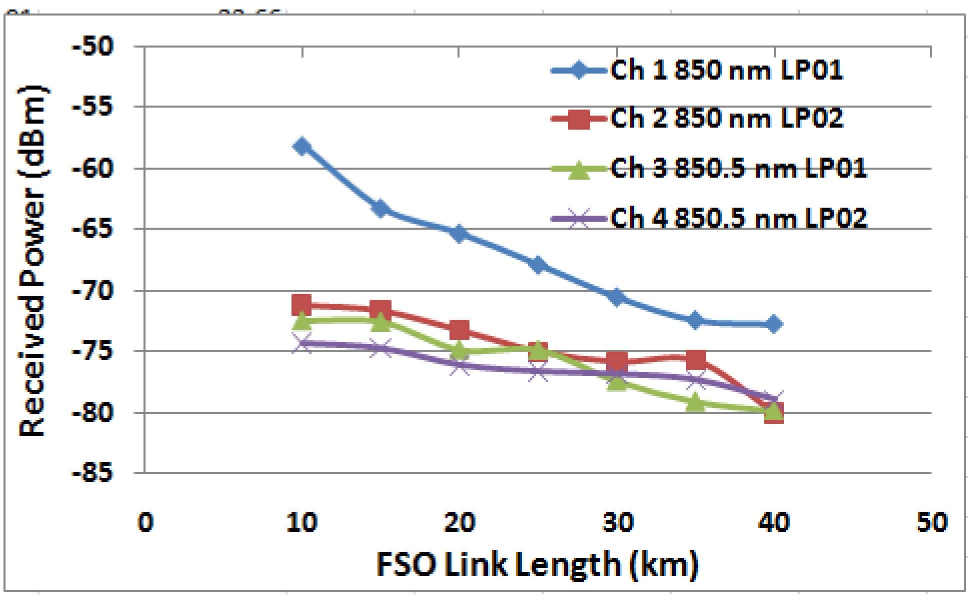


Fig. -5 Performance of different channels at varied FSO distances in terms of Received power

Table 1 represents the values of SNR and received power at different Ro-FSO distances

Distance (km)	Ch 1 SNR (dB)	Ch 2 SNR (dB)	Ch 3 SNR (dB)	Ch 4 SNR (dB)	Ch 1 Rx power (dB)	Ch 2 Rx power (dB)	Ch 3 Rx power (dB)	Ch 4 Rx power (dB)
10	35.63	28.78	27.7	25.81	-58.12	-71.2	-72.4	-74.3
15	32.08	28.13	27.46	25.27	-63.24	-71.66	-72.5	-74.7
20	30.73	26.73	25.12	23.89	-65.31	-73.26	-74.8	-76.1
25	27.66	24.98	25.18	23.36	-67.87	-75.01	-74.81	-76.63
30	26.26	24.15	22.55	23.14	-70.53	-75.84	-77.4	-76.85
35	24.8	24.24	20.91	22.66	-72.41	-75.75	-79.08	-77.33
40	22.61	22.2	20.04	17.4	-72.72	-80.06	-79.82	-78.97

Figure 6 shows the constellation diagrams for (a) ch1 850 nm LP01 (b) ch2 850 nm LP02 (c) ch3 850.5 nm LP01 (d) ch4 850.5 nm LP02 at 10 km and (e) ch1 850 nm LP01 (f) ch2 850 nm LP02 (g) ch3 850.5 nm LP01 (h) ch4 850.5 nm LP02 at 35 km. It is observed from the Figure 6 that more error vector magnitude can be seen in case of all the four channels at distance 35 km but very less EVM is reported at 10 km.

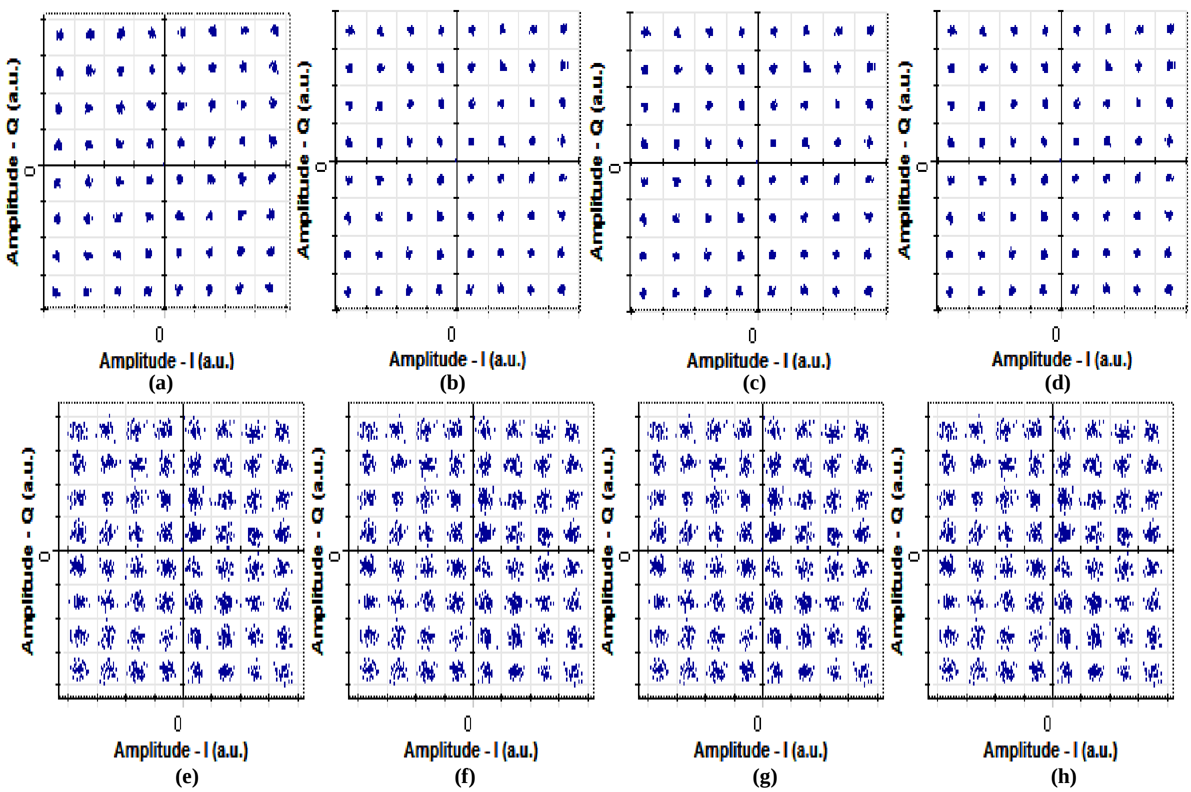


Fig. 6- Constellation diagrams for (a) ch1 850 nm LP01 (b) ch2 850 nm LP02 (c) ch3 850.5 nm LP01 (d) ch4 850.5 nm LP02 at 10 km and (e) ch1 850 nm LP01 (f) ch2 850 nm LP02 (g) ch3 850.5 nm LP01 (h) ch4 850.5 nm LP02 at 35 km

Parameter Name	**Ch1** Value	**Ch2** Value	**Ch3** Value	**Ch4** Value
log of Estimated Symbol Error at	-3.320603485197657	-3.240828333640332	-3.161612506520289	-3.170598349831591
Estimated Symbol Error at User	0.0004779654613085171	0.0005743434417529885	0.0006892670113983982	0.0006751521424997754
Q Factor from Estimated Symbol	3.487196528312564	3.435406480862377	3.392248107987222	3.392248107987222
Error Vector Magnitude at User	0.06608808445010411	0.06325172264579761	0.06638558469475249	0.06184884336781885

Fig. 7- Values of Q factor and Symbol error at 35 km FSO link

Acceptable Q factor in multi level modulation is ≥3 and it is observed from Figure 7 that all the channels are in acceptable limit at 35 km. However further increase in distance makes system out of acceptable range of Q factor.

The observed radio frequency (RF) spectrum at a Ro-FSO distance of 35 km is shown in Figure 8. It demonstrates the successful formation of an RF band on the receiving end, which is then broadcast on the transmitter end. Channels transmitted in LP 01 mode have highest power.

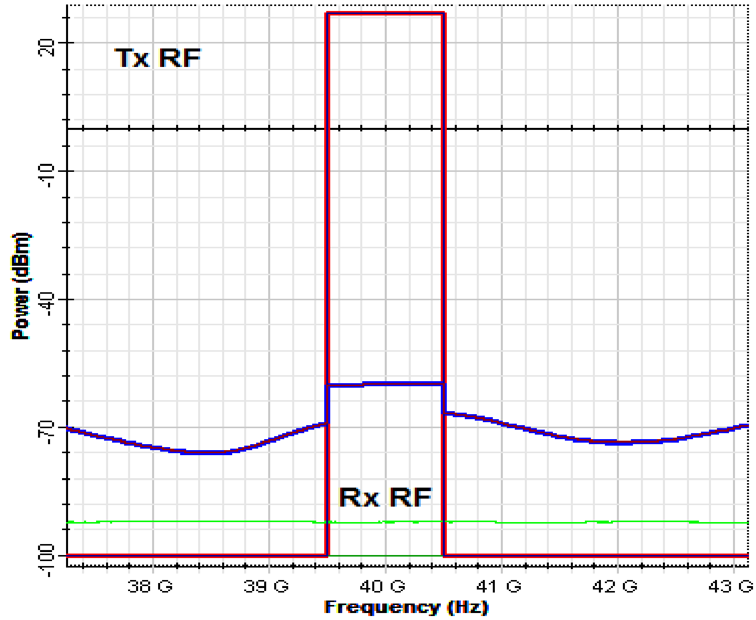


Fig. 8- RF spectrum comparisons at transmitter and receiver for Ch1

Table 2 depicts the comparison of existing work and proposed work in terms of data rate, capacity, modulation, distance, SNR and received power etc. It is observed that proposed system is better than existing work.

Table 2 Comparison of proposed work with existing work

Parameters	**Existing work [14]**	**Proposed work**	**Percentage Improvement**
Data rate	20 Gbps/channel	24 Gbps/channel	20%
Total capacity	80 Gbps	96 Gbps	20%
Modulation	4-QAM-OFDM	64-QAM-OFDM	---
Ro-FSO distance achieved	30 km	35 km	16.66%
Channel spacing (reduced)	1 nm WDM	0.5 nm DWDM	50%
SNR (dB) at 30 km	24.26 (maximum) at ch 1 for 20 Gbps	26.26 (maximum) at ch 1 for 24 Gbps	8.24%
Received power at 30 km	-75.73 dB (maximum) at ch 1 for 20 Gbps	-70.53 dB (maximum) at ch 1 for 24 Gbps	6.8%

4. Conclusion

In this work, hybrid MDM-DWDM is adopted to transmit four high speed channels, with each one has a capacity of 24 Gbps up-converted into 40 GHz mm wave, over 35 km FSO link. 64 QAM and OFDM is used for encoding the 24 Gbps data. For DWDM scheme − 850 nm and 850.5 nm and for MDM-LP 01 and LP 02 modes are used. All the channels are transmitted successfully up to 35 km FSO link with acceptable SNR (~ 20 dB). Beyond that distance, SNR and received power degrades below the acceptable values.

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