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Mode Division Multiplexing of LG and HG modes in Ro-FSO

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***Abstract*— Radio-over-free-space-optics (Ro-FSO) is a strong contender for providing a ubiquitous platform for seamless integration of high capacity radio and optical networks without expensive optical fiber cabling. This work presents mode division multiplexing of LG and HG modes in a 40 GHz Ro-FSO transmission system to realize 4 x 20Gbps over a free space optical link under clear weather conditions. The signal-to-noise-ratio, received power and constellations will be analyzed.**

***Keywords*— Ro-FSO, mode division multiplexing, Hermite-Gaussian mode, Laguerre-Gaussian mode**

Introduction

The rise in cloud computing trends, adoption of smart phones and deluge of multifarious online multimedia services have led to a 30-fold rise in mobile data traffic in the last 15 years and is projected to grow another ten-fold in the five years [1]. The surge in mobile subscribers and data bandwidth to 2.5 exabytes the end of last year poses the issue of radio frequency (RF) spectrum scarcity among wireless operators and intense competition for bandwidth [1-3]. An elegant solution for spectrum scarcity is Ro-FSO. In Ro-FSO, subscribers transmit RF signals via a high-speed optical carrier without expensive RF licensing or optical fiber cabling or, thus accelerating the rollout of wireless network infrastructure [4-7]. Ro-FSO technology can be used for exploiting a different segment of the electromagnetic spectrum for the mobile backbone, thus alleviating RF spectrum congestion issues in current wireless networks. Ro-FSO can be utilized for a number of processes such as RF up-down conversion, handoff, switching, coding and multiplexing, either centralized or shared among all base stations [8-9]. Compatible with existing mobile cellular

architectures, Ro-FSO features the following advantages: a) distribution of RF signals at high bandwidth, b) low attenuation losses, and c) low power consumption [8-9].

Recent Ro-FSO advancement feature experimental measurements [10-11] and statistical modeling [12-13] under various atmospheric turbulence and scintillation effects. To increase the capacity of Ro-FSO systems, multiplexing in the wavelength [14], intensity [15] and phase [16] dimensions have been demonstrated. The eigenmode dimension is to date relatively untapped for multiplexing data streams in Ro-FSO systems. In mode division multiplexing (MDM), eigenmodes are used to drive multiple data streams through a single channel. In optical fiber communications, MDM has been implemented by means of spatial light modulators [17-19], optical signal processing [20-23], few mode fiber [24-25], photonic crystal fibers [26] and modal decomposition methods [27-28] yet MDM is still unexploited in Ro-FSO systems.

This paper aims to explore the performance of MDM of Laguerre-Gaussian (LG) and Hermite-Gaussian (HG) modes in a Ro-FSO system over a FSO link of 40 km for the first time, with each 40GHz optical channel carrying 7.5 GHz radio sub-channels at data rate of 20 Gbps.

The remainder of the paper is organized as follow: Section II elucidates the main principles of the MDM model and simulation parameters. Section III describes the results and discussions, followed by the conclusion in Section IV.

MDM System Description

The proposed model for MDM of LG and HG modes in Ro-FSO is designed in OptiSystem 13 [28], as shown in Fig.1. The proposed architecture comprises four independent

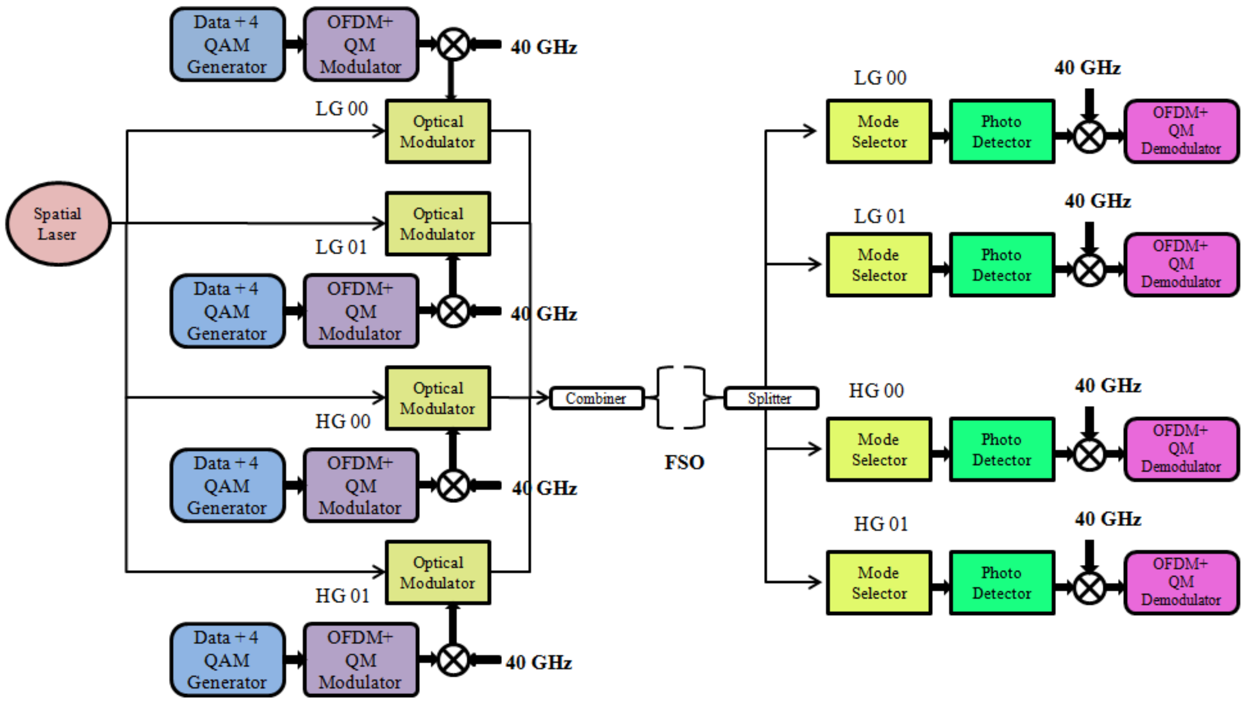

Fig. 1 Proposed MDM in Ro-FSO system

orthogonal frequency division multiplexing (OFDM) subcarrier channels, each carrying distinct 20 Gbps data stream over a 40GHz optical spatial carrier on four different laser modes, LG 00 mode, LG 01 mode, HG 00 mode and HG 01 mode derived by continuous wave (CW) laser and multiplexed over free-space, as shown in Fig. 2.

The LG mode is described mathematically [29] as:

$$\psi_{m,n}(r,\varphi)=\left(\frac{2r^2}{\omega_o^2}\right)^{\left|\frac{n}{2}\right|} L_m^n\left(\frac{2r^2}{\omega_o^2}\right)\exp\left(\frac{r^2}{\omega_o^2}\right)\times \exp\left(j\frac{\pi r^2}{\lambda R_0}\right)\begin{Bmatrix}\sin\left(|n|\varphi\right), n\ge 0\\ \cos\left(|n|\varphi\right), n\ge 0\end{Bmatrix} \qquad (6)$$

where m and n represent the azimuthal and radial indices respectively, R is the radius of curvature, ω_o is the spot size and L_m^n is the Laguerre polynomial. The HG mode is described mathematically [29] as:

$$\psi_{m,n}(r,\phi)=H_m\left(\frac{\sqrt{2}x}{w_{o,x}}\right)\exp\left(-\frac{x^2}{w_{o\,x}^2}\right)exp\left(j\frac{\pi x^2}{\lambda R_{o\,x}}\right)\times H_n\left(\frac{\sqrt{2}y}{w_{o,y}}\right)\exp\left(-\frac{y^2}{w_{o\,y}^2}\right)\left(j\frac{\pi y^2}{\lambda R_{o\,y}}\right) \qquad (7)$$

where m and n represent mode dependencies on the x- and y-axes, R is the radius of curvature, ω_o is the spot size; H_m and H_n are the Hermite polynomials. Four separate 20Gbps four-level quadrature amplitude modulated (QAM) sequences are generated with 2 bits per symbol. Each of the QAM sequences is then modulated on to OFDM 512 sub-carriers using 1024 fast Fourier transform (FFT) points. The four sets of OFDM subcarriers are then modulated at 7.5 GHz using a quadrature modulator (QM). The quadrature-modulated signals are then transmitted over four optical carriers using a Lithium Niobate modulator at 40 GHz with each optical carrier propagated on a different mode from the laser. The four modes comprise the LG mode 00, LG mode 01, HG mode 00 and HG mode 01. The four QM signals are propagated on four modes are then multiplexed and transmitted over a 40km FSO channel.

A spatial Avalanche photodetetector (APD) and a 40 GHz optical carrier is used to retrieve the four MDM signals, which are mode-division demultiplexed based on mean-squared error minimization of the spatial intensity distribution. A semiconductor optical amplifier (SOA) with an injection current of 0.5A is used for post amplification. The APD transmitter and the receiver apertures are 20 cm and 30 cm respectively. For down-conversion, the electrical signal is then fed to a 7.5 GHz QM demodulator. For data recovery, this signal is further fed to an OFDM demodulator and QAM decoder. Clear weather condition is assumed.

Results and discussion

Fig. 2 reveals the signal-to-noise ratio (SNR) and total received power from our proposed Ro-FSO transmission system under clear weather conditions. From the comparison of SNR and received power of all four LG and HG modes in Fig. 2, the LG 00 mode performs the best, followed by the HG 00 mode, LG 01 mode and HG 01 mode.

From Fig. 2(a) and Fig. 2(c), the SNRs for Channel 1 (LG 00 mode) and Channel 2 (LG 01 mode) are significantly higher than the SNRs for Channel 3 (HG 00 mode) and Channel 4 (HG 01 mode). The SNR deteriorates with distance with the SNR for SNR for Channel 1 (LG 00 mode) at 34.11dB, 30.81dB and 23.17dB respectively for a free-space link of 10km, 30km and 50km respectively whereas for Channel 2 (LG 01 mode), the SNR values are significantly lower, i.e.18.11dB, 13.22dB and 5.12dB respectively for an free-space link of 10km, 30km and 50km respectively. For Channel 3 (HG 00 mode), the SNR values are higher than the SNR values for Channel 2 (LG 01 mode) at 32.11dB, 26.23dB and 19.11dB respectively for a free-space link of 10km, 30km and 50km respectively. Channel 4 (HG 01 mode) has the worst performance, with SNR values of 8.75dB, 2.89dB and 0dB at free-space lengths of 10km, 30km and 50km respectively.

The received power is depicted in Fig. 2(b) and Fig. 2(d). Channel 1 (LG 00 mode) and Channel 2 (LG 01 mode) are more robust compared to Channel 3 (HG 00 mode) and Channel 4 (HG 01 mode). From Fig. 2(b) and Fig. 2(d), the values of total received power for Channel 1 are -63.11dBm, -69.54dBm and -76.11dBm for a free-space link of 10km, 30km and 50km respectively. For Channel 2, the total received power is -81.12dBm, -86.11dBm and -94.32dBm for a free-space link of 10km, 30km and 50km respectively. For Channel 3, the total received power is -67.11dBm, -73.44dBm and -80.11dBm for a free-space link of 10km, 30km and 50km respectively. Channel 4 has the worst performance with the total power at -91.22dBm, -93.44dBm and -100dBm for a free-space link of 10km, 30km and 50km respectively. This indicates that Channel 1 achieves 50km and Channel 2 achieves 40km with acceptable SNR and total received power. On the other hand, Channel 3 is extended to 50km whereas Channel 4 is extended to 10km with acceptable SNR and total received power.

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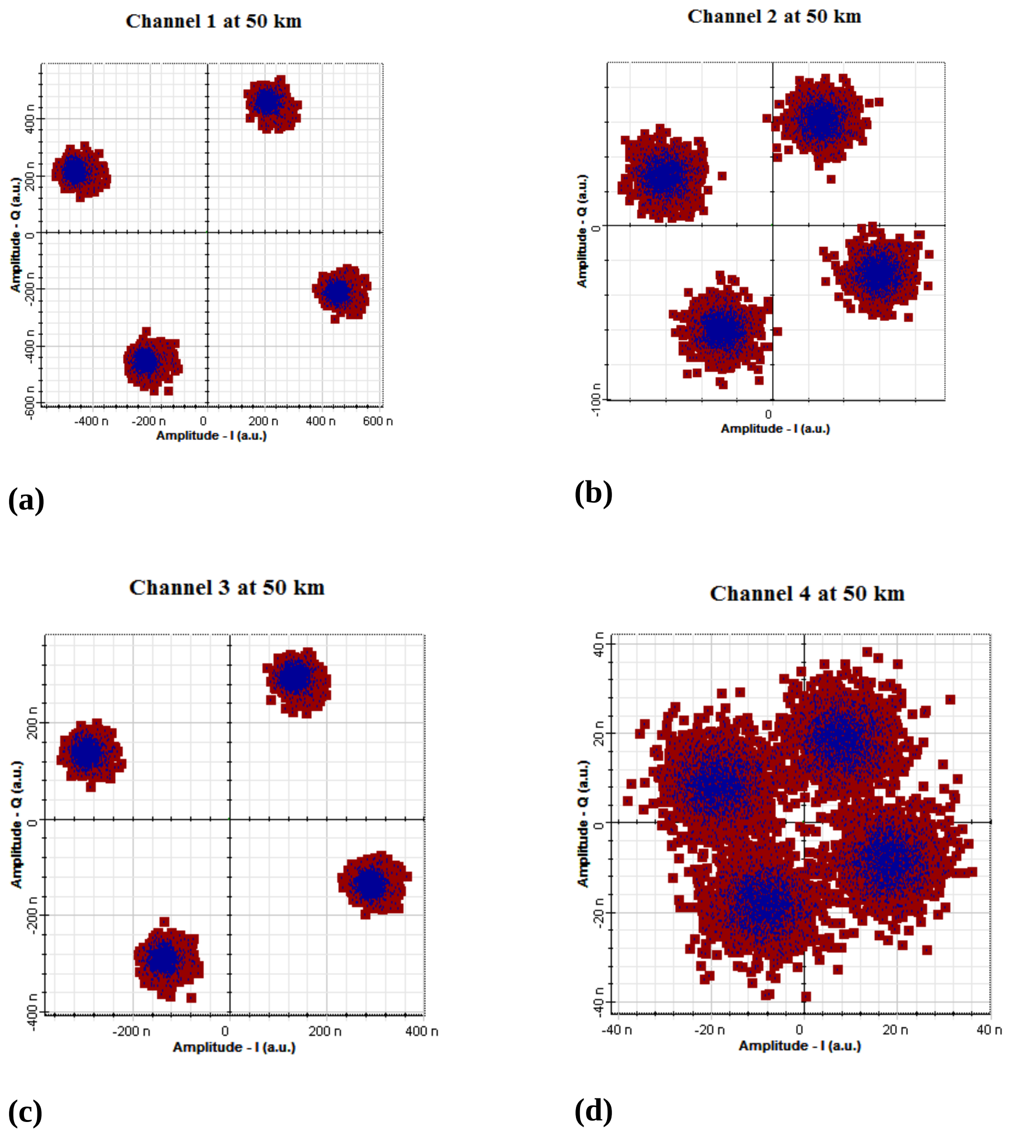

Fig. 3 Measured Constellations at 50km (a) Channel 1 (b) Channel 2 (c) Channel 3 (d) Channel 4

Fig 3 shows the measured constellations at a distance of 50km which confirms that signal degradation is more severe in Channel 4 compared to Channel 1, 2 and 3

Conclusions

This work adopts MDM for transmitting 7.5GHz radio subcarriers on 2 LG modes and 2 HG modes through a Ro-FSO system, each mode propagating at 20Gbps on a 40GHz optical carrier over a free-space link of 40km under clear weather condition. From our results, it is concluded that the HG 01 mode is the most severely affected by multipath fading, followed by LG01, HG00 and LG00. Under clear weather conditions, the free-space link lengths for both Channel 1 propagating LG 00 mode and Channel 3 propagating HG 00 mode are increased to 50km, the free-space link length for Channel 2 propagating LG 01 is extended to 40km whereas the free-space link length for Channel 4 propagating HG 01 mode is extended to 10km with acceptable SNR and total received power.

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