Comparison of Laguerre-Gaussian and Hermite–Gaussian Modes for Optical-CDMA over Multi-Mode Fiber

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Abstract. Optical fiber became essential in telecommunication networks long-distance data transmissions because of its great features such as large bandwidth and long transmission distance. However different profile mode in the optical fiber communication system has different features that provide better results through Multi-mode fiber (MMF). This paper proposes a comparison of different modes for optical code division multiple access (Optical-CDMA) based on one dimension zero cross-correlation (ZCC) code over multi-mode fiber (MMF) transmission system for short haul-local area network. Furthermore Optical-CDMA system transmitted data over using three Laguerre-Gaussian modes (LG 01 LG 02 and LG 0 3) and compare with three Hermite–Gaussian modes (HG 01 HG 02 and HG 0 3) based on 1D-ZCC codes. Over different distance comparison of different modes in Optical-CDMA has evaluated the performance based on eye diagrams bit-error rates (BER) and Q-Factor measurement. The findings show that the proposed system demonstrates good performance over more distance MMF based on Laguerre-Gaussian modes.

1. Introduction

In the last decades the demand for faster internet becomes crucial due to a large amount of internet connected device. Furthermore with the increased use of multimedia applications such as live sharing video and streaming and direct to home television services the demand for bandwidth requirement by end-users has also increased [1-3]. The scholars paid attention to find clever solutions on how to meet the need. These efforts led to the inventing fiber optic technology that enables achieving high capacity demand [4]. In an optical fiber there are two kinds of medium such as single-mode fiber (SMF) and multi-mode fiber (MMF). SMF differs than MMF with a small core diameter; however MMF allows more light paths to propagate. In MMF the different paths are known as modes in waveguides. Modes are amplitude distribution and spatial phase that propagate unaltered in the waveguide and are orthogonal to one another. The modes can then be exploited as independent channels [5]. According to Shannon limitation [6 7] the capacity increases with a signal to noise ratio [8]. Similarly over the last ten years the growth of per capita IP and Internet traffic has followed a curve of steep growth. Globally beginning with (8GB) in 2014 while per capita Internet traffic it is expected to become (22GB) by 2020.
In this respect the monthly per capita Internet traffic was 1GB in 2008 contrasted with 10 MB in 2000 [1]. The communication system using SMF will reach capacity margins in the near future [2-3]; this will increase the needs to use the MMF due to its extremely high bandwidth. Therefore to transfer a larger amount of data it is necessary to enhance the capacity of fiber optic. Nowadays several techniques are available such as time-division multiplexing access (TDMA) orthogonal frequency division multiple access (OFDMA) wavelength division multiple access (WDMA) and optical code division multiple access (optical-CDMA) [9-13]. Optical-CDMA has been implemented to enhance the capacity of data transmission and security for fiber optic communication [14-15]. The optical-CDMA is a scheme that assigns an individual sequence or optical code to every user enabling simultaneous access of multiple users to the optical channel. Specifically the assigned optical code is used with different spectrum modulation to spread the data. Before transmitting over the optical channel this information is code division multiplexed and then receive it the multiplexed information and correlates it with the authorized signature sequence [15]. Multiple users accessing the channel are only able to extract the original information when their optical orthogonal codes match [15-16]. Different modes are needed to be multiplexed onto optical fiber to increase the total throughput for Optical-CDMA. Consequently leading to improve the capacity and bandwidth demand in future information networks and to utilize the optical fiber’s available bandwidth. Laguerre-Gaussian (LG) [11] and Hermite-Gaussian (HG) [17-22] are the most common modes used in optical communication. In this paper different modes are investigated to compare the performance of the MMF in Optical-CDMA based on 1D-ZCC code. Additionally two systems with different modes LG and HG modes are compared. The rest of the paper is structured as follows. Section 2 describes Optical-CDMA simulation. Section 3 presents analysis results and discussions of LG & HG modes: Optical-CDMA. The conclusion of this work is provided in Section 4.

2. Optical-CDMA Simulation and Description

Figure 1 illustrated the comparison of LG and HG modes for Optical-CDMA based on one-dimension ZCC code over MMF transmission system. We designed and simulated the system using opti-system [23-26] and MATLAB [27] software.

![Figure 1. Simulation setup of Comparison of different modes in Optical-CDMA.](image-url)
The comparison of different modes in Optical-CDMA system consists of three parts: 1) Transmitter; 2) MMF; and 3) Receiver. Specifically the transmitter parts are divided into five components as follows:

1. Spatial vertical-cavity surface-emitting laser (spatial VCSEL).
2. Encoding.
3. Pseudo random binary sequence (PRBS) generator.
4. NRZ pulse generator.
5. Modulator and power combiner.

Briefly we now describe the components of the transmitter. Firstly spatial VCSEL is used to generate two different sets of modes that operate over one wavelength (1550 nm). Figure 2 presents the generated modes LG 0 1, LG 0 2, and LG 0 3 (i.e. LG modes). Mathematically the LG mode can be defined as follows [28]:

$$
\psi_{m,n}(r,\varphi) = \left( \frac{2r^2}{W_0^2} \right)^{\frac{|n|}{2}} L_m^n \left( \frac{2r^2}{W_0^2} \right) \exp \left( -\frac{r^2}{W_0^2} \right) \exp \left( j \frac{\pi r^2}{2R_0} \right) \begin{cases} \sin(|n|\varphi) & n \geq 0 \\ \cos(|n|\varphi) & n \geq 0 \end{cases} \right)
$$

where m and n represent the X (describes the azimuthal index) and Y (describes the radial index) indexes; R indicates to the radius of curvature; \( W_0 \) is spot size and \( L^n_m \) refers to the Laguerre Polynomial.

Additionally as shown in Figure 3 the other generated set of modes (by spatial VCSEL) are HG 0 1, HG 0 2, and HG 0 3 (i.e. HG modes). The HG mode is mathematically described as follows [28]:

$$
\psi_{m,n}(r,\varphi) = H_m \left( \frac{\sqrt{2x}}{W_0^2} \right) \exp \left( -\frac{x^2}{W_0^2} \right) \exp \left( j \frac{\pi x^2}{2R_0^2} \right) H_n \left( \frac{\sqrt{2y}}{W_0^2} \right) \exp \left( -\frac{y^2}{W_0^2} \right) \exp \left( j \frac{\pi y^2}{2R_0^2} \right)
$$

Similar to LG mode m and n represent the X and Y index that describe the mode dependencies for the X and Y-axis; R indicates to a radius of curvature and \( W_0 \) is the spot size. However \( H_m \) and \( H_n \) are the Hermite polynomials.
Figure 3. Spatial visualizer of three HG modes.

The second component of the transmitter is encoding which is based on one-dimension ZCC code (used for three users). PIIN is strongly related to MAI in Optical-CDMA system because of the overlapping spectra from different users [14 15]. The 1D-ZCC code can be formulated in a matrix form (K × L) where K row is a number of the users and L element is written as the code length. Additionally the ZCC codes are implemented for three users. This code can be written in a unit code matrix as follows:

\[
ZCC(w = 2) = \begin{bmatrix}
1 & 0 & 0 & 1 & 0 & 0 \\
0 & 1 & 0 & 0 & 1 & 0 \\
0 & 0 & 1 & 0 & 0 & 1
\end{bmatrix}
\]  

(3)

The input signal is generated using three PRBS at the third component of the transmitter. It is generated from the data generator at 1.866 Gbps. The fourth component is a non-return-to-zero (NRZ) signal generating sequence. Lastly Mach-Zehnder modulator and the power combiner are allocated at the transmitter as a fifth component.

As mentioned earlier the second part of our system is the fiber optic link. Here we used MMF and the maximum distance link is 8 km. Lastly the third part of the system is a receiver that consists of the following components:

1. The incoming signal from MMF is power splitter into three users and three decoders.
2. Photo-detector (PIN) is used to perform the conversion from optical to electrical domain.
3. Low pass Bessel filter (LPBF).
4. The last component is the performance analyzer.

Finally Table 1 summarizes the parameters of comparison of different modes in Optical-CDMA
Table 1. Parameters of comparison of different modes in Optical-CDMA.

| Component Name | Parameters | Value      |
|----------------|------------|------------|
| Spatial VCSEL  | Power      | 1dBm       |
|                | Wavelength | 1550 nm    |
|                | Laguerre-Gaussian | 0 1 0 2 0 3 modes |
|                | Hermite–Gaussian | 0 1 0 2 0 3 modes |
| Multimode      | Attenuation | 0.25 dB–Km |
|                | Core radius | 50 nm      |
| APD            | Responsivity | 1 A/W      |
|                | Dark Current | 10 A       |

3. Optical-CDMA Results and Description

In the experiments we measured BER Q-Factor and eye diagram the comparison of different modes in Optical-CDMA based on 1D-ZCC code MMF transmission system. Now we analyze these performance parameters to determine how much improvement can get from our system. In the beginning the BER and Q-Factor of LG modes in Optical-CDMA based on 1D-ZCC code are calculated in Figures 4 and 5. Specifically we calculate both BER and Q-Factor of (USER 1: LG 0 1 USER 2: LG 0 2 and USER 3: LG 0 3) over the distances (2 Km 3 Km 4 Km 5 Km 6 Km 7 Km 8 Km and 9 Km) respectively. The figures demonstrate that BER and Q-Factor are accepted over the distances (from 2 Km until 8 Km) whereas they are not accepted at distance of 9 Km.

Figure 4. BER results of (USER 1: LG 0 1 USER 2: LG 0 2 and USER 3: LG 0 3) over different distances.
In the second part of the experiments as shown in Figures 6 and 7 we measured BER and Q-Factor of HG modes in Optical CDMA over the distances 2 km to 9 km respectively. Specifically we evaluated the performance for USER 1: HG 0 1 USER 2: HG 0 2 and USER 3: HG 0 3 over the distances 2 km to 9 km. Similar to LG modes BER and Q-Factor showed an accepted performance over the distances 2km to 8km. However the present unaccepted performance at a distance of 9 km.

**Figure 5.** Q-Factor results of (USER 1: LG 0 1 USER 2: LG 0 2 and USER 3: LG 0 3) over different distances.

**Figure 6.** BER results of (USER 1: HG 0 1 USER 2: HG 0 2 and USER 3: HG 0 3) over different distances.
Figure 7. Q-Factor results of (USER 1: HG 0 1 USER 2: HG 0 2 and USER 3: HG 0 3) over different distances.

As shown in Figure 8 we evaluated the eye diagram of the comparison of different modes in Optical-CDMA over MMF at a distance of 8 km. We calculate the eye diagram of (USER 1: HG 0 1 USER 2: HG 0 2 and USER 3: HG 0 3) and (USER 1: LG 0 1 USER 2: LG 0 2 and USER 3: LG 0 3) respectively. It is important to mention that all channels have clean and open eyes. The outcomes demonstrate that the results are better with using of LG mode for Optical-CDMA based on 1D-ZCC code compared to HG modes.

Figure 8. Eye diagram of (USER 1: HG 0 1 USER 2: HG 0 2 and USER 3: HG 0 3) and (USER 1: LG 0 1 USER 2: LG 0 2 and USER 3: LG 0 3) at a distance of 8 km.

Finally in Figures 9 and 10 we measured BER and Q-Factor of LG and HG modes in Optical-CDMA based on 1D-ZCC code over MMF. The results demonstrate that LG modes are better than HG modes in Optical-CDMA system based on 1D-ZCC code over MMF.
4. Conclusion
In this paper we studied the comparison of LG and HG modes for Optical-CDMA based on one-dimension ZCC code over MMF transmission. Different modes can be used as a data carrier with different 1D-ZCC code in Optical-CDMA to improve the bandwidth. These modes should be selected carefully to get the longest possible distance with the lowest BER and Q-Factor. The outcomes demonstrated that it is possible to get a successful transmission data over 8 km MMF link with acceptable BER Q-Factor and eye diagrams. However at a distance of 9 km the results are not acceptable due to nonlinearity and distortion in MMF. This issue can be solved by using artificial intelligence (AI) to overcome the nonlinearity issue and enable the MMF to transmit the data over more distance. Therefore as future work we will work on applying AI algorithms in our system.

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