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Performance Analysis of New 2D Spatial OCDMA Encoding based on HG Modes in Multicore Fiber

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Abstract—**This paper presents a pioneering 2D spatial Optical Code-Division Multiple Access (OCDMA) encoding system that exploits Mode Division Multiplexing (MDM) and Multicore Fiber (MCF) technologies. This innovative approach utilizes two spatial dimensions to enhance the performance and security of OCDMA systems. In the first dimension, we employ Hermite-Gaussian modes (HG00, HG01, HG11) to modulate each user's signal individually. This unique approach offers a robust means of data transmission while ensuring minimal interference among users. The second-dimension leverages MCF encoding, introducing two incoherent OCDMA codes: the Zero Cross Correlation (ZCC) code (λc=0) and the ZFD code (λc=1). These codes are thoughtfully designed and simulated, taking into account their cross-correlation properties to guarantee minimal interference and heightened data security. To assess the efficiency of this novel OCDMA encoding system, we implemented simulations with three active users using the Opti system software. At the transmitter end, each user's signal is modulated individually by their designated HG mode (HG00, HG01, HG11), resulting in separate channels. Subsequently, at the multicore fiber, each user's data is encoded with a unique code-word, and they are directed through specific core groups, ensuring data isolation and integrity. In this paper, the BER and eye pattern are examined with respect to different parameters such as data rate and distance. At a distance of 5 km and data rate of 10 Gbit/s, a BER value around 10^{-70} is achieved.**

Keywords—**Hermite-Gaussian modes; multicore fiber; mode division multiplexing; code division multiple access.**

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I. Introduction

High-capacity network infrastructure is crucial with the plethora of devices deployed for cyber physical systems and real-time analytics. Mode division multiplexing (MDM) has garnered considerable attention as a propitious approach for increasing data capacity by multiplexing data channels on orthogonal modes, in conjunction with wavelength division multiplexing [1-3] and polarization division multiplexing [4]-[6]. Various types of modal bases, such as Laguerre-Gaussian [7]-[9], Hermite-Gaussian [10]-[12], Bessel-Gaussian [13-15], orbital angular momentum (OAM) modes[16], [17], and linearly polarized mode groups [18], [19] have been investigated for MDM.

Increasing data capacity and ensuring secure multiple access is vital for meeting growing data demands, optimizing network efficiency, enhancing security, ensuring scalability, and enabling the smooth functioning of various services and applications in today's interconnected world. Consequently, a critical challenge in optical fiber communications is the capability to secure multiple users access over the same optical fiber with minimal crosstalk between multiple users. Code division multiple access (CDMA) has attracted attention recently due to its decoding simplicity from unipolar and real-valued signals, compared to other more complex sparse coding approaches [20]. CDMA is an attractive technology for designing a secure medium access control protocol for multiple users in optical fiber concerning various channels for degrees of freedom. This includes polarization channels, which have been considered for CDMA multiple access. However, in polarization channels, continuous random fluctuations in the polarization of the optical fiber are challenging to control [21]. On the other hand, using dense wavelengths for multiple channels may affect spectral utilization and result in exorbitant implementation costs [22].

Consequently, to address these limitations, CDMA has been carried out in conjunction with MDM to increase the capacity of optical transmission systems without additional spectral utilization and to improve security against physical layer attacks. In [23], a hybrid system combining SAC-OCDMA, FSO, and MDM are proposed. In this system, Zero Cross-Correlation (ZCC), Random Diagonal (RD), Multi Diagonal (MD), and Enhanced Double Weight (EDW) codes are used for SAC-OCDMA, considering different atmospheric turbulences. For MDM, Laguerre Gaussian (LG) modes are employed to construct a system with ten channels, each carrying 10 Gb/s of data. In [24], a comparison study was made between two codes of OCDMA: multi-diagonal (MD) and ZCC. Additionally, a proposal was made for utilizing Laguerre Gaussian (LG) modes (specifically LG01, LG 02, and LG 03) in a multi-mode fiber (MMF) transmission system. In [25], performance and security analyses of the SAC-OCDMA/MDM system over optical wireless communication (OWC) were conducted. Additionally, a novel code called Zero Cross Correlation Resultant Weight (ZCCRW) with a capacity of 100 Gbps was introduced and compared to previous codes (RD, EDW, and DDW) through simulations. The study also compared hybrid modulations using LG and HG modes to determine the optimal modulation scheme.

The works in [23]-[25] require complex signal processing for decoding spatial modes within a wireless medium or a single-core fiber. In this paper, to address this issue, we exploit a multicore fiber (multicore fiber) in generating code words, where power sharing among specific cores reduces crosstalk between modes within a mode group. Multicore fibers have garnered pervasive significance in space division multiplexing, where the mode and the core multiplicities can be integrated for capacity enhancement [26]. The novel contribution of this paper is to represent the first dimension of the CDMA encoding by a particular Hermite-Gaussian mode to avoid interference among users inside the multicore fiber. The second dimension of the CDMA will be derived from the various cores of the multicore fiber. The potential application of the proposed architecture is improved link reliability for last-mile connections.

The paper proceeds as follows. The second section describes the proposed encoding method based on HG Mode and multicore fiber for Optical CDMA technique. In the third section of the simulation, the created system and the used parameters are shown. In the fourth section, the BER and eye diagram results are represented. Finally, the last section shows the conclusion.

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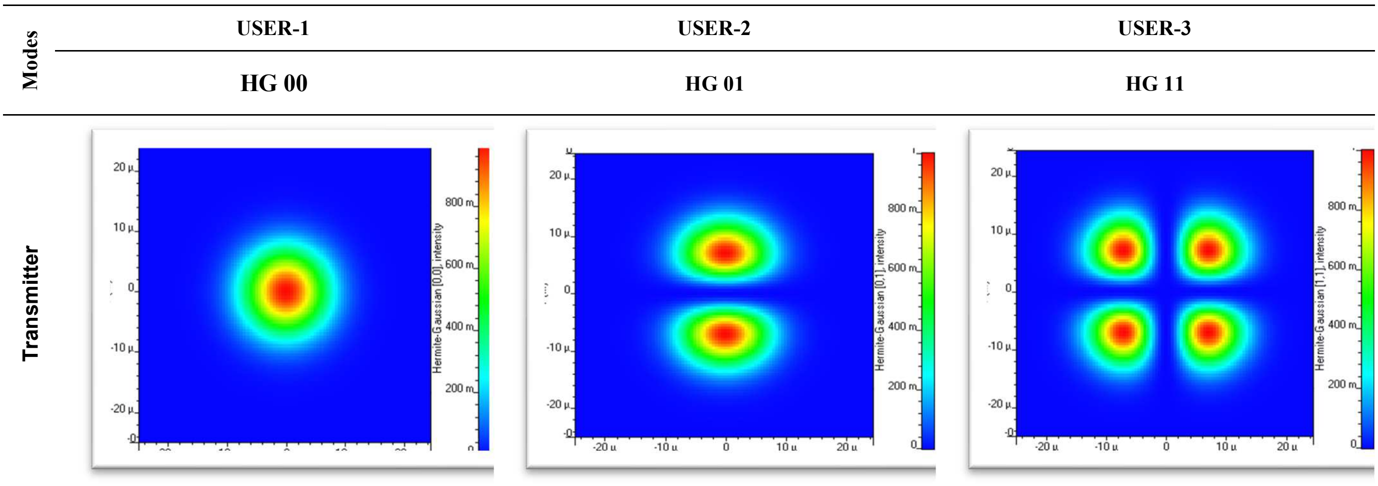
II. Material and Method

This paper presents a proposed approach for encoding in two-dimensional (2D) optical code division multiple access (OCDMA). The approach utilizes mode division multiplexing and multicore fiber to generate the code words. In the first dimension, each user is uniquely identified by a specific Hermite-Gaussian (HG) mode. This identification method prevents crosstalk when sharing the same cores among different users. Complementing this, various groups of cores of the multicore fiber are harnessed for the second dimension. The proposed method is applied for the incoherent OCDMA encoding with unipolar code. Herein, we will present the proposed HG modes for this paper and focus on the mathematical model for the multicore fiber encoding method. Herein, a system of three users will be presented for simulation. Therefore, three HG modes are required, which are HG00 for the first user, HG01 for the second user, and HG11 for the last user. Fig. 1 shows the HG modes for all users before launching in the multicore fiber at the transmitter side and after (at the receiver part).



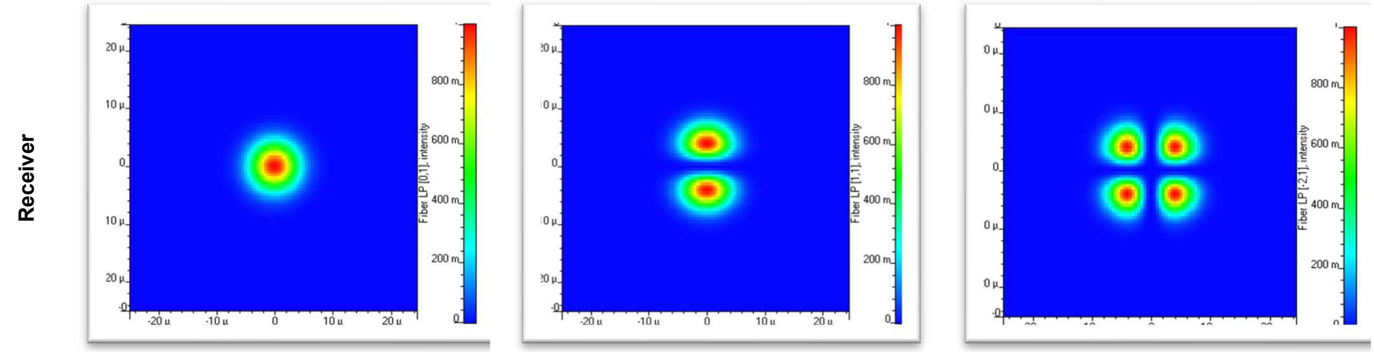


Fig. 1 HG modes before and after MCF.

We observe the mode's power diminution due to different effects, such as the attenuation inside the multicore fiber (MCF) (2.61 dB/km). In SDM, the most essential device is the spatial multiplexer (SMUX), where its main functionality is converting optical signals from a SMFs bundle into separate cores inside the multicore fiber [27]. Fig. 2. shows an SMUX schematic prototype.

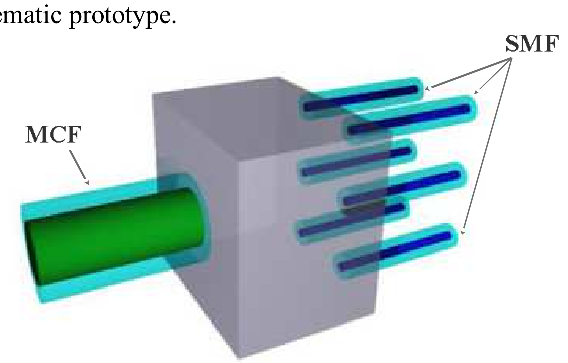


Fig. 2 Spatial multiplexer

The SMUX is represented mathematically by a matrix [27], as shown below in (1):

$$\begin{bmatrix} C_1 \\ C_2 \\ \vdots \\ C_N \end{bmatrix} = \begin{bmatrix} \gamma_{1,1} & \gamma_{1,2} & \cdots & \gamma_{1,N} \\ \gamma_{2,1} & \ddots & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{N,1} & \vdots & \cdots & \gamma_{N,N} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_M \end{bmatrix} \quad (1)$$

Γ: SMUX transfer matrix

Cn represents n-th core, N is the total cores number, Im is the launch field from m-th SMF, and M is the total fibers number. The total number of cores and fibers is equal (*N*=*M*). The SMUX transfer matrix contains the overlap integral at the face of multicore fiber and it can be calculated as follows:

$$\gamma_{i,j} = \frac{\int E^*_{Launch,i} \cdot H_{Spatial,j} dA}{\sqrt{\int E^*_{Launch,i} \cdot H_{Spatial,i} dA} \sqrt{\int E^*_{mode,i} \cdot H_{Spatial,i} dA}} \leq 1 \quad (2)$$

where:

- $E^*_{Launch,i}$ is the transverse electric field of the *i*th launch field at the SDM fiber facet.
- The notation * points out the complex conjugate.
- $H_{Spatial,i}$ is the transverse magnetic field of the jth spatial channel.
- A represents the fiber cross-sectional area.

The performance of SMUX is tested according to some parameters, such as coupler insertion loss (CIL), which is the average insertion loss in all spatial channels, and core dependent loss (CDL), which is the loss difference between the worst and best cores [27].

In MCF, crosstalk (XT) is considered the most sensitive issue for a few modes-multicore fiber transmission. XT may be divided into two types. The first type is the intra-core crosstalk, and it is caused by the coupling among modes within each single core due to the fiber flaws. The intra-core crosstalk varies according to a number of transmitted modes in a single core. Eq. 3 can define the modal crosstalk when only the first three modes are exploited:

$$XT = -30 + 10\log(L) \quad (3)$$

where *L* represents the length of the multicore fiber. The second type is the inter-core crosstalk, which is generated from mode coupling (homo-mode coupling and hetero-mode coupling) [28]. In this paper, we have proposed uncoupled cores multicore fiber. For that, *Γ* in Eq. 1 is rewritten as a diagonal matrix. The parameters CIL and CDL are calculated with the diagonal entries of *Γ*.

$$\begin{bmatrix} C_1 \\ C_2 \\ \vdots \\ C_N \end{bmatrix} = \begin{bmatrix} \gamma_{1,1} & 0 & 0 & 0 \\ 0 & \gamma_{2,2} & 0 & 0 \\ 0 & 0 & \ddots & \vdots \\ 0 & 0 & \cdots & \gamma_{N,N} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{bmatrix} \quad (4)$$

$$CIL = \sum(\gamma^2_{n,n}) / N \quad (5)$$

$$CDL = \max(\gamma^2_{n,n}) / \min(\gamma^2_{n,n}) \quad (6)$$

The launch field *the HG modes can represent me*, it is described mathematically as shown below [29]:

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

where *m* and *n* represent mode dependencies on the *x*- and *y*-axes, H_m and H_n are the Hermite polynomials, w_o is the spot size and *R* is the radius of curvature.

In SAC-OCDMA, each code is characterized by (*N, w, λc*): *N* is the code length, *w* is the code weight, and *λc* is the maximum cross-correlation [30]. In this approach, *N* can be considered the total cores number, w is the number of used cores by one user, and λc represents how many user signals propagate through the same core. The SAC-OCDMA based on [31] is encrypted on the multicore fiber, where a core group substitutes the weight, w by a wavelengths group within the multicore fiber. In this work, ZCC and ZFD codes [31] are exploited to assess this proposed method's efficiency. Each code is represented by [$K*N$] matrix. For the example of K=3 and w=3, the number of total cores is represented by N and it is modeled as follows:

$$N_{ZCC} = K * w \tag{8}$$

$$N_{ZFD} = 3 + fact(w-1) + D \tag{9}$$

TABLE I
CORES USED FOR EACH USER

Users	ZCC code (λc=0)	ZFD code (λc=1)
User 1	C_1 C_4 C_7	C_1 C_4 C_5
User 2	C_2 C_5 C_8	C_2 C_5 C_6
User 3	C_3 C_7 C_9	C_3 C_6 C_7

Table 1 shows the cores we will exploit for each user in the ZCC and ZFD codes cases. A schematic diagram for system architecture for the novel 2D spatial OCDMA encoding based on HG modes in multicore fiber is shown in Fig. 3 for enhanced link reliability (in terms of BER, bit rate, and eye diagram).

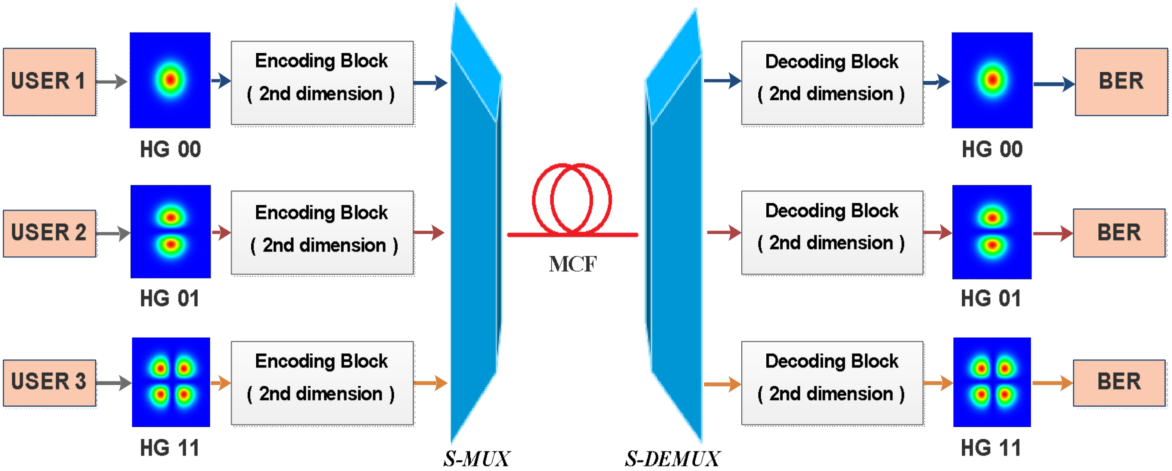


Fig. 3 OCDMA system architecture based on HG mode and MCF.

In order to prove the performance of this proposed encoding approach, we have created the system architecture for three users in the OptiSystem software. The transmission part, a pseudo-random bit data sequence, generates the data, and it is represented in the electrical form by a non-return-to-zero (NRZ) pulse generator. Then, each user signal is characterized by a special mode (Fig. 4) for each user.

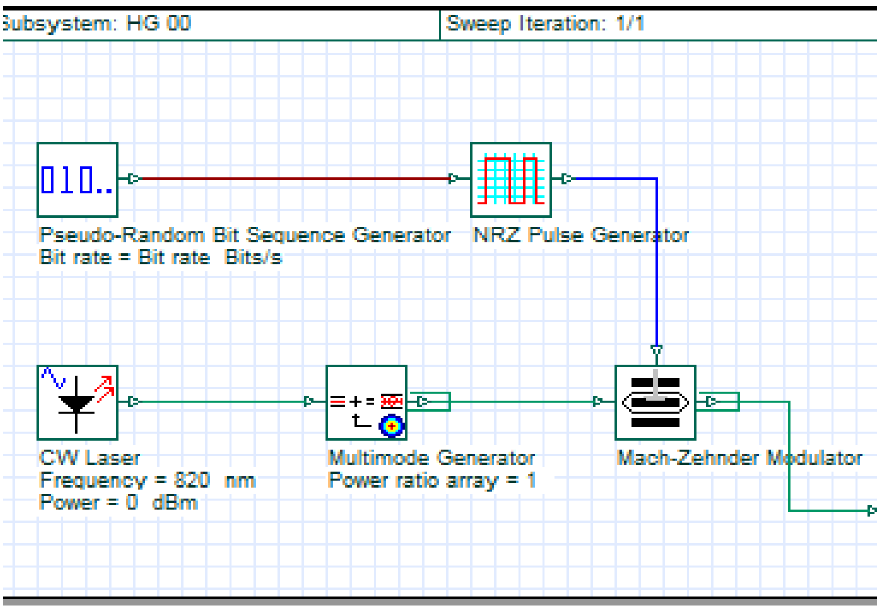


Fig. 4 Data generation of HG00 mode

At the channel, all signals will cross through the multicore fiber, where an overlap integral value of one is taken. Each utilizer will exploit his code-word, represented by a specific core group (Table 1). The propagation effects (linear and nonlinear) will touch the multicore fiber inside. Table 2 shows the parameters used for the simulation.

TABLE II

KEY PARAMETERS IN THE SIMULATION

Parameter	Value
Number of utilizers	03
Signal Data	128 $PN\ sequence$
Format of the signal	NRZ
External modulator extinction ratio	30 dB
Attenuation	2.61 dB/Km
Dark current	10 nA
Thermal noise coefficient	$1.8e-023\ W/Hz$
Receiver filter bandwidth	$0.75 \times Bit\ Rate$
Reference wavelength	820 nm
Spot size (w0)	10 μm
Core radius	25 μm

At the reception, the signals at the multicore fiber output will be combined according to each code word, and then each signal must be passed by a mode selector to recover each utilizer's HG mode. The spatial photodetector is used to detect each signal. A fourth-order Bessel low pass filter filters the resultant one to reject the interference and noise in the information spectrum [31]. Finally, a BER analyzer is used to check the system performance.

III. RESULT AND DISCUSSION

This encoding method contains three users and exploits mode division multiplexing and multicores fiber. In this part, the simulation results of the proposed OCDMA system according to some parameters are shown and discussed below. These parameters are the BER and the eye diagram versus the fiber length (or distance) and the data rate.

First, the bit error rate (BER) is analyzed concerning the fiber length, keeping a fixed data rate of 10 Gbit/s and an effective source power of 0 dBm. Fig. 5 illustrates the relationship between BER and fiber length. The simulation results demonstrate that a distance of up to 5 km has been achieved. Comparing the BER values between ZCC code and ZFD code, it is observed that the ZCC code performs better relationship between BER and fiber length. The simulation results demonstrate that a distance of up to 5 km has been achieved. Comparing the BER values between ZCC code and ZFD code, it is observed that the ZCC code performs better.

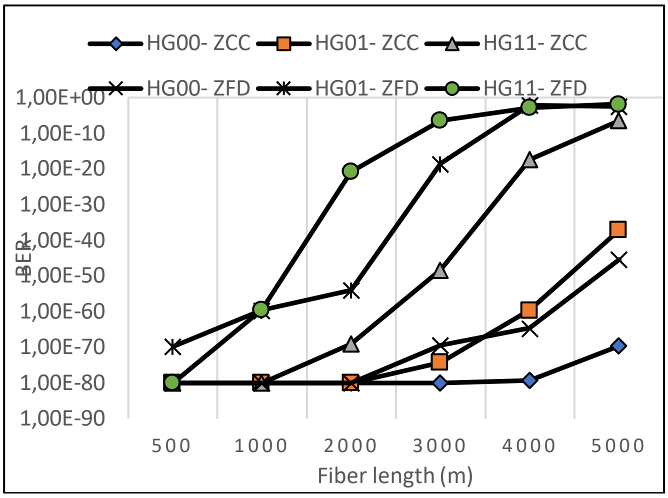
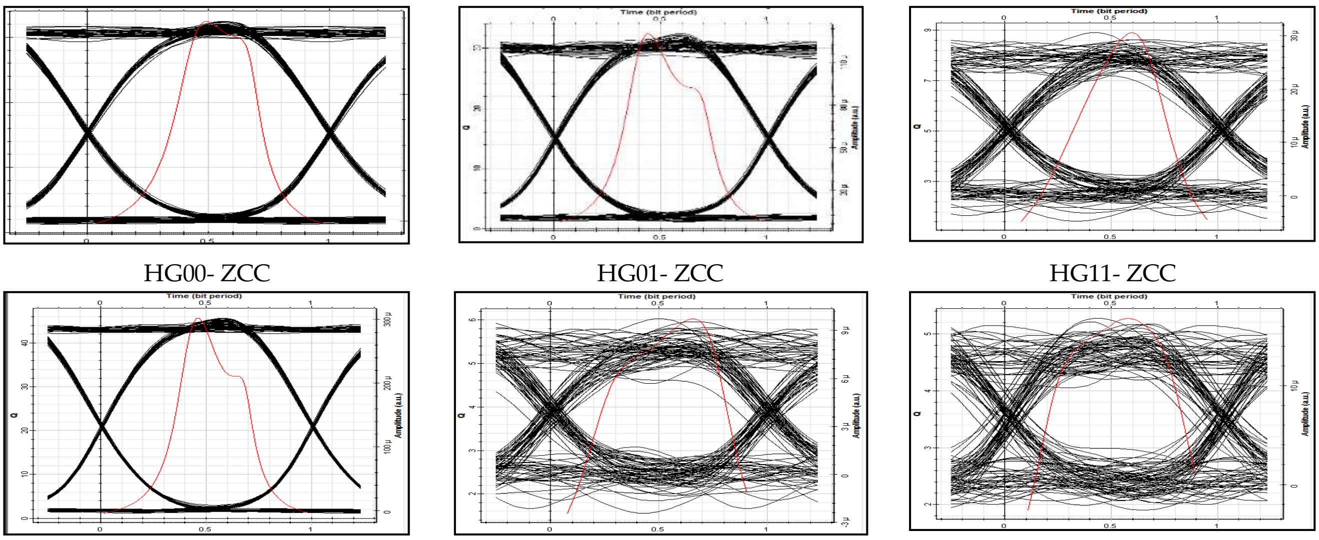


Fig. 5 BER versus fibre length

This suggests that utilizing codes with zero cross-correlation is preferable in this encoding method, as the ZFD code is affected by intra-core crosstalk. Additionally, it is noted that the HG00 mode outperforms the HG01 and HG11 modes in both the ZCC and ZFD cases, exhibiting lower BER values. The increase in BER with the extension of the fiber length is attributed to various propagation effects such as dispersion, attenuation, and Kerr effects. These factors weaken the transmission performance, leading to higher error rates as the signal propagates over longer distances. Fig. 6 shows the eye diagram for a distance of 3 km and a data rate of 10 Gbit/s. It shows that the eye diagrams of the ZCC code are more open than those of the ZFD code, and HG00 gives the best eye diagram in both codes. The second simulation shows the BER versus data rate (See Fig. 7). At the first step, we fixed a distance of 4.5 km and an effective power source of 0 db (See Fig. 8). Then, we adjusted the data rate from 0.5 Gbit/s to 10 Gbit/s. We observed the same trends as in the first simulation in this simulation.



HG00- ZCC HG01- ZCC HG11- ZCC

HG00- ZFD HG01- ZFD HG11- ZFD

Fig. 6 Eye diagram at 3 km (10 Gbit/s)

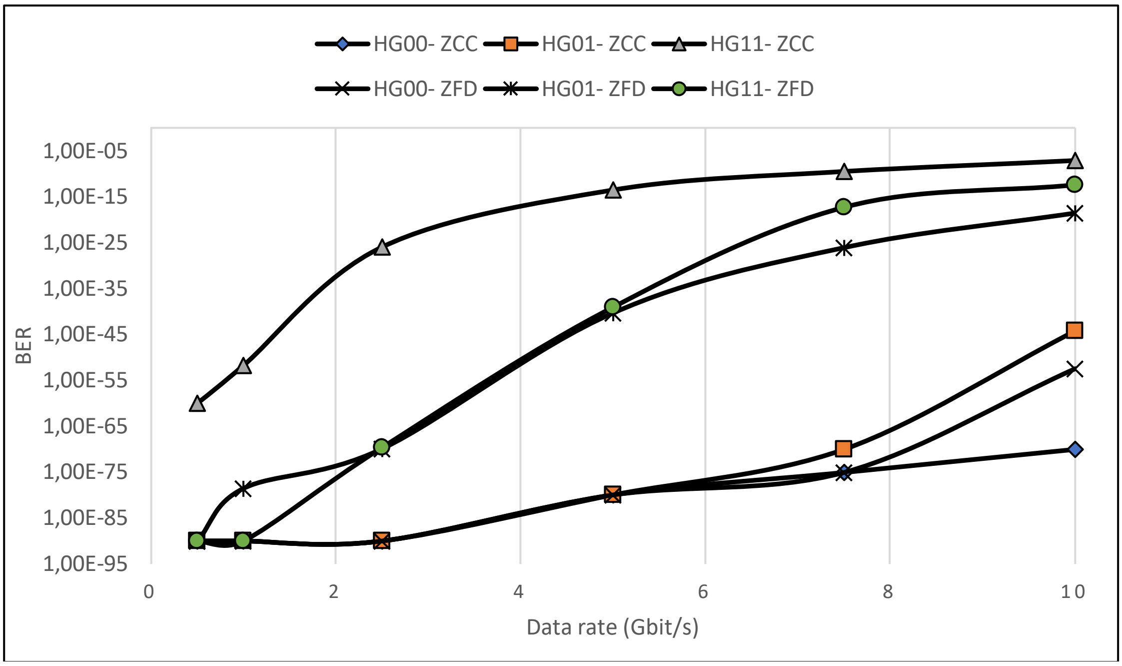


Fig. 7 BER versus data rate

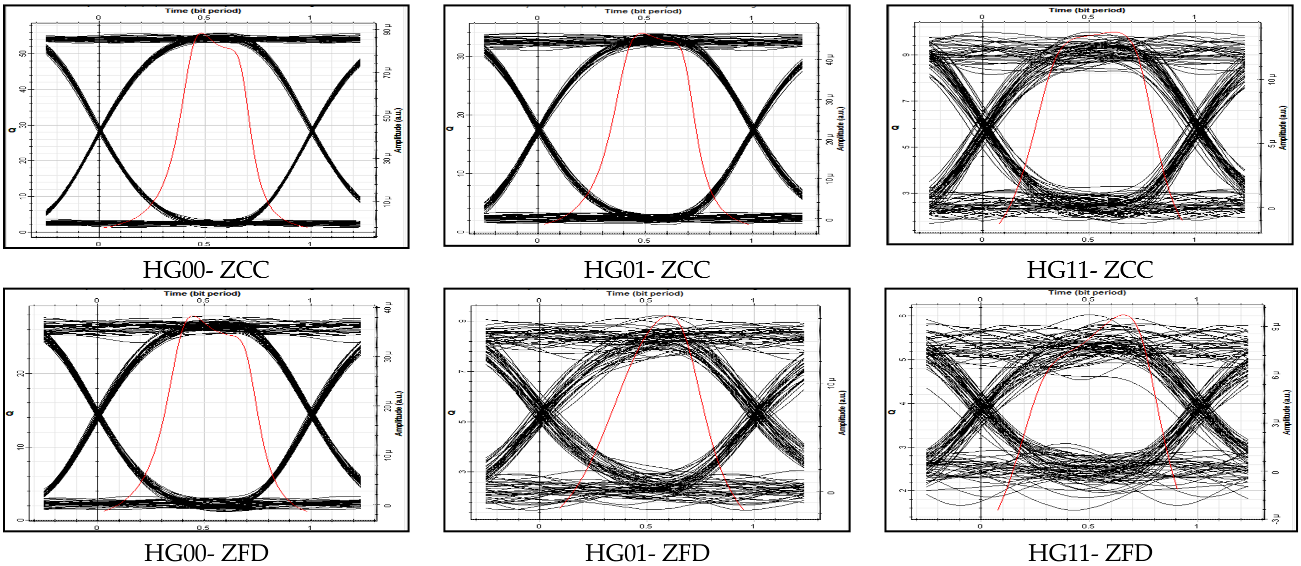


Fig. 8 Eye diagram at 4.5 km (5 Gbit/s)

IV. Conclusion

In this paper, a novel 2D spatial OCDMA encoding system was designed. This approach is based on mode division multiplexing and multicore fiber. For MDM on the first dimension, Hermite-Gaussian modes were selected, and the data from each user was modulated by its own mode. Following this, in the second dimension, distinct cores of the multicore fiber were encrypted using the ZCC code (λc=0) and the ZFD code (λc=1). In order to examine the efficiency of this novel OCDMA encoding approach for short-distance communications, a system model with three active users was created in Optisystem software. Each user is modulated at the transmitter by HG00, HG01, and HG11. At the multicore fiber, each user is coded by its own code word by the selection of specific core groups to propagate through. This paper examined BER and eye diagrams against data rate and distance parameters.

The obtained results proved the efficiency of this 2D encoding method for the OCDMA system, with the ZCC outperforming the ZFD. Future research in OCDMA should aim to address the remaining challenges in terms of performance, scalability, and compatibility with other networking technologies. By delving into these areas, advancements can be made toward achieving more efficient, secure, and high-capacity OCDMA systems for the ever-growing demands of modern communication networks.

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