Polarization Encoding and Decoding Techniques for a 10 Gbps Hybrid FDW-EDW OCDMA System

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ABSTRACT: Optical Code Division Multiple Access (OCDMA) is a form of multiple access scheme that allows multiple users to share a common fibre. OCDMA utilize codes depicted by optical spectra/spatial properties. There are various types of OCDMA codes. The most typical OCDMA code used are the Double Weight (DW) family code. The DW family code consists of the Modified Double Weight (MDW), the Enhanced Double Weight (EDW), and the recently developed Flexible Double Weight (FDW) code. Each code has its uniqueness in terms of code weight, basic code users, and code length which contributes to the Bit Error Rate (BER) and signal quality at the receiver. The newly proposed system is the Hybrid FDW/EDW code, which combines FDW and EDW codes using the polarization technique. This approach uses FDW and EDW codes to achieve zero cross-correlation properties within the same wavelength. Each user receives a unique codeword that matches a specific polarization state, making them orthogonal. The selected polarizations are 0º and 90º, which ensure minimal cross-correlation between users with different polarizations. The DW code family is considered a non-hybrid system in this research. According to the results obtained in this study, Hybrid systems outperform non-hybrid systems in terms of BER and transmission distance. Hybrid FDW/EDW systems can achieve a range of up to 80 km, while non-hybrid FDW systems can reach up to 60 km, and non-hybrid EDW systems can reach up to 50 km. This indicates that the proposed hybrid system shows a 60% improvement over non-hybrid EDW systems and a 33.33% improvement over non-hybrid FDW systems.

KEYWORDS: Optical Code Division Multiple Access, Flexible Double Weight, Enhanced Double Weight, Multiple Access Interference, Phase Induced Intensity Noise, Bit Error Rate.

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I. INTRODUCTION

Optical Code Division Multiple Access (OCDMA) is one of the multiple access schemes that employ spectral/spatial properties in form of code for data transmission. OCDMA makes use of the available optical bandwidth more efficiently than other multiple access schemes such as Time Division Multiple Access (TDMA) and Wavelength Division Multiple Access (WDMA) (Zouine et al., 2008; Jellali, Ferchichi & Najjar, 2021). The advantages of OCDMA systems over the conventional multiple access schemes include channel allocation flexibility, asynchronous access, privacy enhancement, and network capacity increase (Vyas et al., 2011; Cherifi et al., 2023). Various types of codes such as Modified Double Weight (MDW) code, Enhanced Double Weight (EDW) code, and Flexible Double Weight (FDW) code are introduced in OCDMA to mitigate the effect of Multiple Access Interference (MAI) and Phase-Induced Intensity Noise (PIIN) (Abdullah et al., 2007, 2008; Kumawat et al., 2017; Ammar et al., 2023). The code length and weight are important elements of system architecture since they directly impact the bit error rate (BER) and the throughput of OCDMA systems (Anuar et al., 2013; Tseng et al., 2021; Ullah et al., 2024).

Spectral Amplitude Coding (SAC) represents a frequency domain coding method utilized in OCDMA systems, and it is aimed at mitigating the challenges posed by MAI within prior incoherent systems (Zaccarin & Kavehrad, 1993). SAC shares similarities with Spectral Phase Coding (SPC) in its approach to discern frequency components from a broadband optical source. However, the distinctive feature of SAC lies in the utilization of spectral amplitude encoders for individual code channels, wherein specific frequency components are selectively blocked or transmitted. In contrast, SPC relies on an SPC grid to induce various phase shifts across spatially resolved spectral components. Based on a research paper by Kakaee et al. (2012), the Hybrid system proposed is a combination of OCDMA and Wavelength Division Multiple Access (WDMA) system. Random Diagonal (RD) code was used as OCDMA codes. The purpose of this Hybrid system is

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to combine 2 distinct systems to pass through a single fibre. OCDMA and WDMA exhibit distinct performance characteristics when combined by a multiplexer. WDMA can cover the longest transmission distance than OCDMA in a Hybrid OCDMA/WDM system.

The proposed system utilizes a polarization encoding technique, also known as Spectral Polarization Coding (SPC), to compress the code, enabling support for a greater number of users with shorter code lengths. Polarization refers to a property of electromagnetic waves that characterize the direction of the transverse electric field, which can be divided into two orthogonal components (X and Y). The optical signal is characterized by its intensity, wavelength, and polarization. Currently, intensity is employed for encoding the information to be conveyed, while polarization serves to distinguish multiple channels. Polarization encoding is achieved by transmitting independent data in each of the two orthogonal linear polarization states within the optical fibre, thereby doubling the spectral efficiency of single-polarization transmissions (Dhaam et al., 2020; Sahraoui et al., 2021).

It is crucial to note that SAC-OCDMA coding operates within the wavelength domain as opposed to the time domain, highlighting a fundamental departure from traditional coding schemes. This wavelength-based encoding strategy not only distinguishes SAC from its temporal counterparts but also underscores its efficacy in addressing issues related to MAI, thereby contributing to the enhanced performance of OCDMA systems.

The primary aim of this research is to develop a new DW family code by combining the FDW and EDW code called FDW/EDW Hybrid OCDMA code by using a novel polarization encoding technique to overcome the problem faced in previous systems. By applying the polarization encoding technique, the code is compressed, allowing it to support a larger number of users while simultaneously shortening its length. The polarization technique can reuse optical spectrum hence compress the code length of the code and increase the number of users. The bit error rate (BER) and signal-to-noise ratio (SNR) determine the quality of data transmission within a specific distance and a given number of users (Ahmed et al., 2019; Martinez et al., 2022). The acceptable value of BER is 10^{-9}. If the BER is higher than 10^{-9}, the number of bit losses during transmission will be high (Imtiaz et al., 2020; Bazan, 2022). The newly proposed hybrid FDW/EDW code, using polarization encoding technology, is specifically engineered to accommodate a larger user base, resulting in an increased data transfer rate and reduced power usage. When considering costs and complexity, SPC OCDMA is a cost-effective and practical option for modest to medium-sized networks. It requires fewer components, utilizes simpler technology, and is relatively easy to maintain. On the other hand, hybrid OCDMA systems offer a more balanced and flexible design, making them easier to manage and scale compared to the more single-dimension focus of the SPC system. The hybrid approach makes more efficient use of resources by combining two distinct codes within the same system using the polarization technique. This technique greatly enhances the transmission distance in OCDMA by reducing signal degradation, minimizing interference, and improving spectral efficiency. This innovation is in line with the main objective of improving the efficiency and efficacy of OCDMA systems, therefore contributing to advancements in optical communication technology. The paper is organized as follows: it starts with an introduction to OCDMA code, followed by the design of a hybrid system, performance analysis, results and discussion, and concludes with a summary.

II. OCDMA CODE

A. Enhanced Double Weight (EDW) Code

The Enhanced Double Weight (EDW) code is an advanced version of the Double Weight (DW) code, characterized by parameters such as code weight (W), number of users (K), code length (N), and cross-correlation (λc). The code weight for EDW code can be of any odd number greater than one. Its representation involves a K x N matrix, where the rows correspond to the number of users and the columns represent the minimum code length in a prescribed order (Hasoon et al., 2006; Abdullah et al., 2008). The number of users is:

$$K = W \tag{1}$$

and

$$N_{\text{EDW}} = \sum_{i=1}^{W} i \tag{2}$$

Equation (2) is the general formula for code length, N in relation to the code weight, W. The impact of code weight on an OCDMA system is significant, as an increased weight leads to improved SNR. The explanation behind this enhancement is that an increase in code weight automatically amplifies the signal power of each user, thereby boosting SNR. EDW codes exhibit excellent cross-correlation properties, as theoretical analysis demonstrates their effectiveness in suppressing phase-induced intensity noise, yielding preferable results (Norazimah et al., 2014).

EDW sets itself apart from DW and MDW in terms of sequence and structure by featuring a unique pattern of 2, 2, 1 instead of the typical 1, 2, 1. Notably, the EDW sequence maintains a cross-correlation of 1 and allows for two overlaps within three columns.

Table 1. Basic EDW code sequence for Weight (W) = 3

	Code Length						
Users	C_5	C_4	C_3	C_2	C_1	C_0	-
1	1	0	1	1	0	0	3
2	1	1	0	0	1	0	3
3	0	0	1	0	1	1	3
-	-	-	-	-	-	-	-
-	2	1	2	1	2	1	-

Referring to Table 1, the EDW code's chip combination sequence follows pattern 2, 1, 2, 1, 2, 1 across the first six columns. This sequence is derived by summing the values of corresponding chips present in every two rows. The arrangement of chips in this specific sequence (2, 1, 2, 1, 2, 1) is designed to ensure that the cross-correlation value remains at 1, allowing only one overlap between two chips (Zahid et al., 2009).

In summary, the EDW code's unique features, including its odd code weight, distinctive sequence pattern, and optimized chip combination sequence, contribute to its superior performance in OCDMA systems, particularly in mitigating phase-induced intensity noise and maintaining favourable cross-correlation properties. In EDW systems, the code length is computed as:

$$N_{\mathrm{EDW}} = 2K + \frac{4}{3}\left[\sin\frac{K\pi}{3}\right]^2 \left[\frac{8}{3}\left(\sin\left[\frac{(K+1)\pi}{3}\right]\right)^2 + \frac{4}{3}\left(\sin\left[\frac{(K+2)\pi}{3}\right]\right)^2\right] \quad (3)$$

For a given code length N_{EDW}, the relationship between the EDW code with a code weight of three and the corresponding number of users K can be established (Al-Khafaji et al., 2012). This relationship implies that the specific code weight of three is a determining factor in configuring the number of users adapted by the EDW code which underlines the connection between these two parameters.

B. *Flexible Double Weight (FDW) Code*

The FDW code represents an improvement over the DW, MDW, and EDW codes, offering enhanced flexibility in terms of code weight. In contrast to its predecessors, the FDW code accommodates both odd (as in the case of EDW) and even (similar to MDW) code weights (Ammar et al., 2023). The FDW sequence closely resembles that of DW, yet with noteworthy augmentations which features a code sequence of 1, 2, 1, ..., 1n. A distinctive characteristic of FDW is its fixed basic user code, which is set at 2, a departure from the previous codes where each weight had a distinct basic user code.

Table 2. FDW code sequence for Weight (W) = 3. (Odd).

	Code Length									
Users	C_9	C_8	C_7	C_6	C_5	C_4	C_3	C_2	C_1	C_0
1	0	0	0	0	0	0	1	0	1	1
2	0	0	0	0	0	1	0	1	1	0
3	0	1	0	1	1	0	0	0	0	0
4	1	0	1	1	0	0	0	0	0	0
-	1	1	1	2	1	1	1	1	2	1

Table 3. FDW code sequence for Weight (W) = 4. (Even).

	Code Length														
Users	**C_{13}**	**C_{12}**	**C_{11}**	**C_{10}**	**C_9**	**C_8**	**C_7**	**C_6**	**C_5**	**C_4**	**C_3**	**C_2**	**C_1**	**C_0**	-
1	0	0	0	0	0	0	0	0	0	1	1	0	1	1	4
2	0	0	0	0	0	0	0	1	1	0	0	1	1	0	4
3	0	0	1	1	0	1	1	0	0	0	0	0	0	0	4
4	1	1	0	0	1	1	0	0	0	0	0	0	0	0	4
-	1	1	1	1	1	2	1	1	1	1	1	1	2		

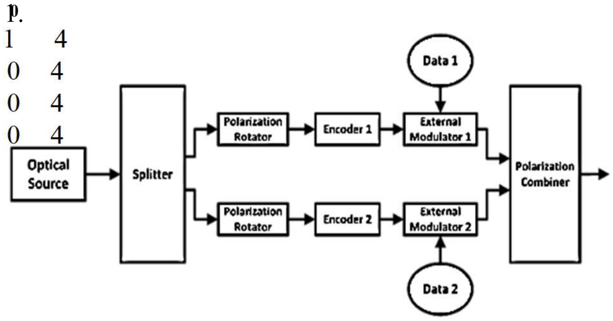
Tables 2 and 3 illustrate the foundational code architecture for FDW, showcasing configurations for odd (W = 3) and even (W = 4) code weights, respectively. This design choice emphasizes the adaptability of FDW code to both odd and even weight scenarios, providing a comprehensive framework for different applications. The provided code sequences in Tables 2 and 3 exhibit a cross-correlation (λc) of one, and with a notable presence of high autocorrelation (λa). The relationship among the variables N_{FDW}, K, and W is concisely expressed through the general formula presented in Eqn. (4).

$$N_{\mathrm{FDW}} = \left[K + \left[\sin\left(\frac{K\pi}{2}\right)\right]^2\right] W + \left[-\frac{1}{2}K - 1.5 - \left[\sin\left(\frac{W\pi}{2}\right)\right]^2 - \frac{1}{2}K\left[cos\left(\frac{K\pi}{2}\right)\right]^2\right] \quad (4)$$

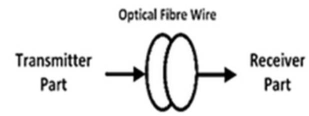
An innovative application of the FDW code involves leveraging its properties within the same wavelength to achieve zero cross-correlation, presenting a novel approach. Unlike other codes within the DW family, FDW stands out as particularly well-suited for Local Area Networks (LANs) which offer the capability to support higher bit rates. This positioning makes FDW a noteworthy choice in scenarios where zero cross-correlation and high bit rates are important considerations, showcasing its versatility and applicability across various communication environments.

III. HYBRID SYSTEM DESIGN

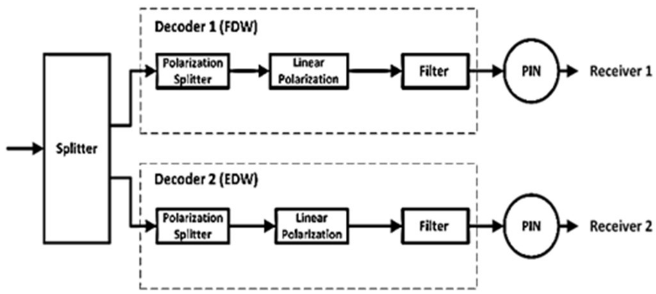
A novel encoding system has been devised based on the fundamental physics of light polarization. Light, being a transverse electromagnetic wave, exhibits electric and magnetic field vibrations perpendicular to each other and in any plane orthogonal to the light's direction of motion (Hong et al., 2023; Abdol et al., 2023; Wu et al., 2024). The innovative approach employs a combination FDW and EDW codes to achieve zero cross-correlation properties within the same wavelength. In this technique, each user is assigned a unique codeword that corresponds to a specific polarization state, making them orthogonal to each other. The polarizations selected are 0º and 90º which means that there is minimal cross-correlation between users with different polarizations. This allows multiple signals to be transmitted simultaneously on the same wavelength without significant interference. Unlike other DW family codes, FDW/EDW Hybrid system is specifically suitable for an access network with high data rates and throughput value. The block architecture of the polarization encoding-decoding scheme is illustrated in Figure 1.



(a)



(b)



(c)

Fig. 1. Block diagram of an OCDMA system implemented with Hybrid FDW/EDW Code: (a) OCDMA transmitter part (b) OCDMA channel/medium (c) OCDMA receiver part

For an OCDMA system with FDW/EDW Hybrid code, each user with an assigned code (designated as basic users, Kb) receives a distinct degree of light rotation through the use of a polarization rotator. This ensures non-overlapping wavelengths, preventing interference with the original code which is presented in Table 4. The combiner consolidates all channels into a single-mode optical fibre, while the splitter organizes data to their respective receivers. A decoding technique involving linear polarization is applied, enabling the filtering of specific degrees of the same wavelength. To evaluate system performance, an analyser is incorporated to assess the BER for each user.

Table 4. 5 Basic user FDW/EDW hybrid OCDMA code.

Degree of Rotation	Code	K_{th}	C_5	C_4	C_3	C_2	C_1	C_0
0°	FDW	1	0	0	1	0	1	1
0°	FDW	2	0	1	0	1	1	0
90°	EDW	3	1	0	1	1	0	0
90°	EDW	4	1	1	0	0	1	0
90°	EDW	5	0	0	1	0	1	1

As shown in Table 4, polarization encoding is a valuable technique in OCDMA systems for achieving zero cross-correlation properties. It leverages the orthogonal nature of different polarization states to enable multiple users to share the same wavelength, improving spectral efficiency and enhancing system security.

IV. PERFORMANCE ANALYSIS

In this section, simulation analysis was performed on FDW, EDW and Hybrid FDW-EDW code using OptiSystem 15 software. These simulations are often conducted under idealized or near-real conditions that take into account various practical factors, such as noise, signal interference, and channel impairments. The comparison is based on the Bit Error Rate transmission distance supported for OCDMA systems. Each DW family code has its uniqueness and advantages as the combination of 2 DW family codes (EDW and FDW) is expected to surpass its predecessor. For the system to work properly, the BER should be less than 10^{-9}. The BER is the ratio of the number of erroneously received bits to the total number of bits transmitted. An oscilloscope was used to generate an eye pattern, which is a visual representation of signal quality to measure the BER. Eye patterns are essential in optical communication systems as they help in detecting distortions and noise that can lead to signal degradation. They provide valuable insight into the overall performance of the communication channel. By examining the opening and closure of the eye pattern, engineers can determine the integrity of the received signal. A wide and well-defined eye indicates a clean and reliable signal, while a distorted or narrowed eye suggests signal degradation. Table 5 shows the typical parameters used in OCDMA systems.

Table 5. Typical parameters used in OCDMA systems.

Parameters	**Unit**
Photodetector quantum efficiency (η)	0.6
Operating wavelength (λo)	1,550 nm
Linewidth Broadband Source	3.75 THz
Dark Current	1 nA
Thermal Noise Coefficient	1 x 10^{-22} W/Hz
Electrical bandwidth (B)	5 GHz
Receiver noise temperature (T_n)	300 K
Receiver Load Resistance (R_L)	1,030 Ohms
Bit Rate	10 Gbps

V. RESULTS AND DISCUSSION

Since the proposed hybrid method is a combination of FDW and EDW, the eye pattern for the hybrid FDW/EDW is divided into two types of decoders which are FDW decoder and EDW decoder. The performance of two distinct systems in a hybrid system using polarization is compared with the sole system (without polarization). The fibre length chosen for comparison of OCDMA systems is 50 km, 60 km, and 80 km. Since it covers the maximum performance threshold for Hybrid and Non-Hybrid systems. There are certain limitations, challenges, and issues that may arise when simulating and comparing hybrid OCDMA and non-hybrid OCDMA systems. In terms of performance, hybrid OCDMA systems may have a greater capacity and spectral efficiency than non-hybrid OCDMA systems. However, achieving these benefits often comes with a trade-off in terms of complexity, latency, and susceptibility to noise and channel impairments. Figures 2 and 3 show the eye pattern of Hybrid FDW/EDW for each system receiver at 80 km with a 10 Gbps bit rate.

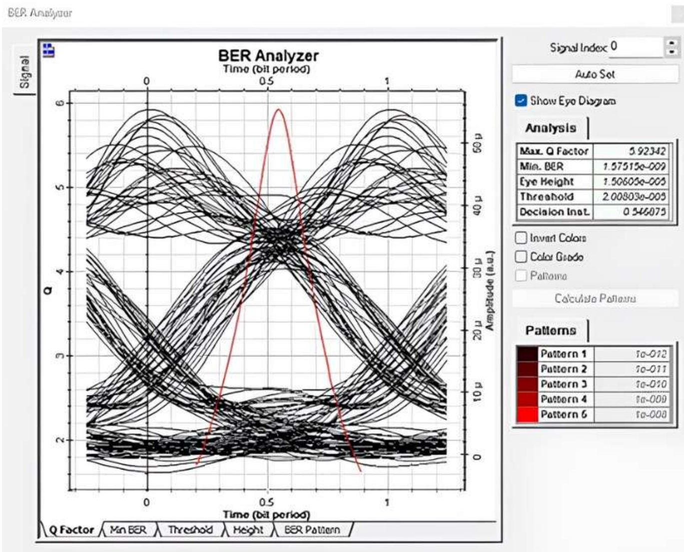


Fig. 2. The eye pattern of Hybrid FDW/EDW at an FDW receiver for 80 km distance with 10 Gbps bit rate.

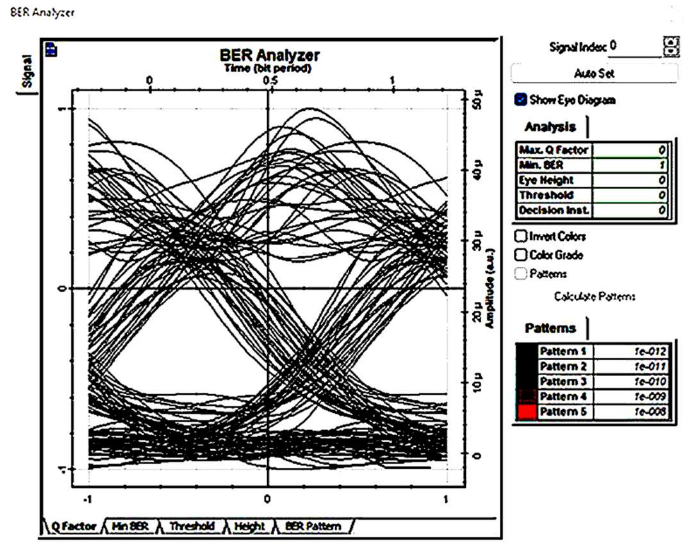


Fig. 4. The eye pattern of non-Hybrid FDW for 80 km distance with 10 Gbps bit rate.

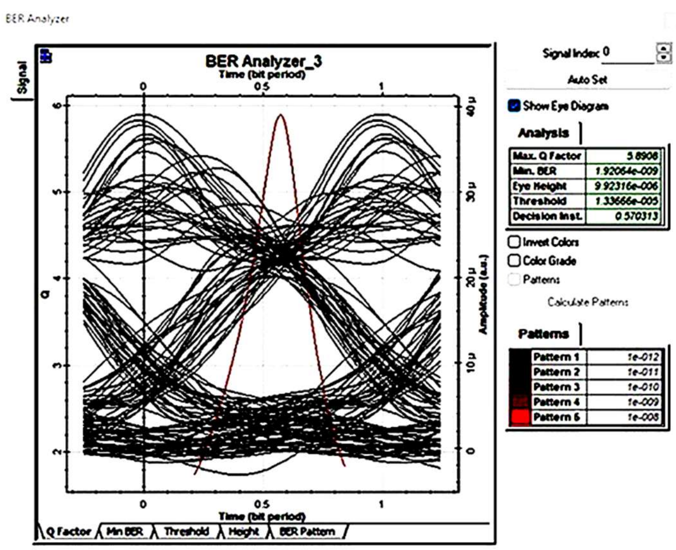


Fig. 3. The eye pattern of Hybrid FDW/EDW at an EDW receiver for 80 km distance with 10 Gbps bit rate.

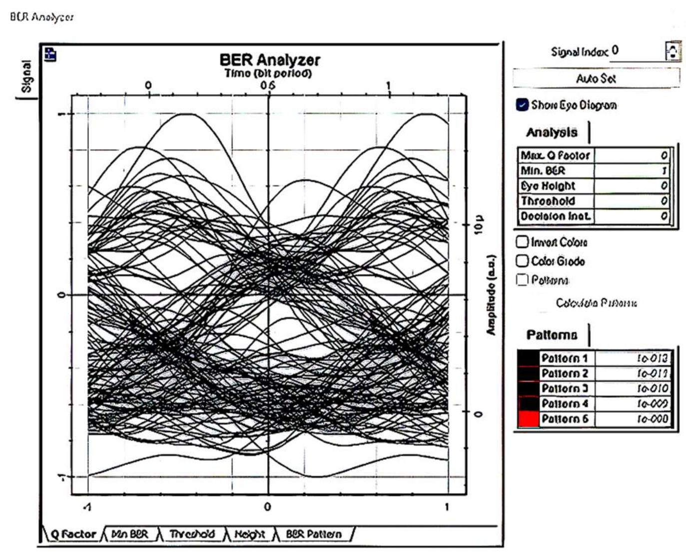


Fig. 5. The eye pattern of non-Hybrid EDW for 80 km distance with 10 Gbps bit rate.

Based on the results shown in Figures 2 and 3, the transmission distance for the hybrid system is 80 km for a 10 Gbps bit rate. The BER for both channels in the hybrid system is 1.57515 x 10^{-9} at the FDW receiver and 1.92064 x 10^{-9} at the EDW receiver. Both results reached the BER threshold as the quality of signal above 80 km is considered not an acceptable BER in OCDMA systems. The combination of FDW and EDW using polarization achieved a stable result for the hybrid system. For the non-hybrid system, the separation of FDW and EDW as a sole system (without polarization) was tested for 80 km with 10 Gbps bit rate and the results are shown in Figures 4 and 5.

Both FDW and EDW Non-Hybrid have BER equal to 1 which indicates the transmission data received are totally error at 80 km. Compared to the hybrid system, the non-hybrid systems have higher BER at 80 km transmission distance and at 10 Gbps bit rate. This is because using polarization doubles the spectral efficiency of single polarization transmission and increases transmission range. To obtain the acceptable BER for non-hybrid FDW and EDW, the measurement of BER acquired at 60 km for FDW and 50 km for EDW are shown in Figures 6 and 7.

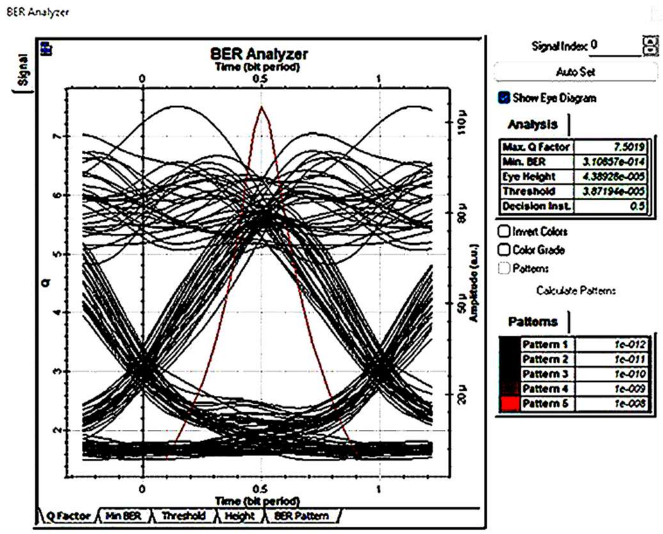


Fig. 6. The eye pattern of Non-Hybrid FDW for 60 km distance with 10 Gbps bit rate.

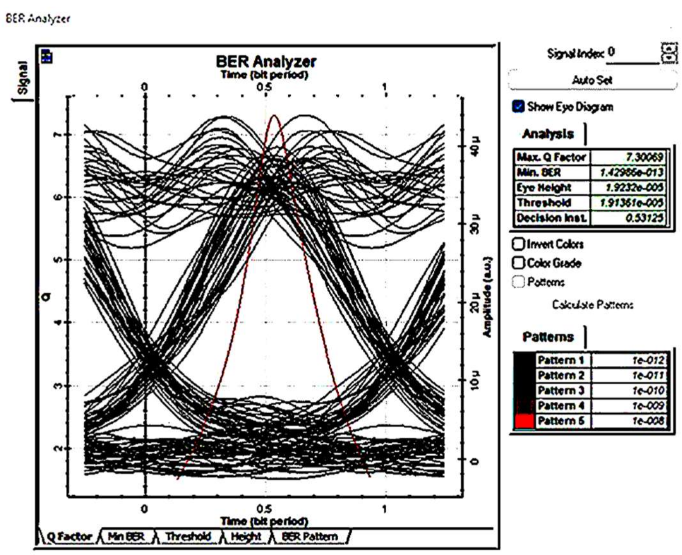


Fig. 7. The eye pattern of Non-Hybrid EDW for 50 km distance with 10 Gbps bit rate.

The results shown in Figures 6 and 7 are the specific distances for individual BER of non-hybrid systems. For further observation, Table 6 provides tabulated data for the performance of the considered OCDMA system in terms of BER and fibre length at10 Gbps bit rate.

Table 6. Performance of Hybrid and Non-Hybrid OCDMA system at 10 Gbps Bit Rate.

OCDMA Codes	Fiber Length (km)	Bit Error Rate (BER)
Hybrid FDW/EDW	80	1.57515×10^{-9}
	60	7.52313×10^{-25}
	50	1.69505×10^{-28}
Non-Hybrid FDW	80	1
	60	3.10857×10^{-14}
	50	2.16074×10^{-15}
Non-Hybrid EDW	80	1
	60	1.60653×10^{-8}
	50	1.42986×10^{-13}

Based on data collected in Table 6, it is proven that Hybrid FDW/EDW has the best performance as it offers a 60% improvement in transmission distance compared to the non-hybrid system. For better understanding, a graphical presentation for hybrid and non-hybrid OCDMA is shown in Figure 8.

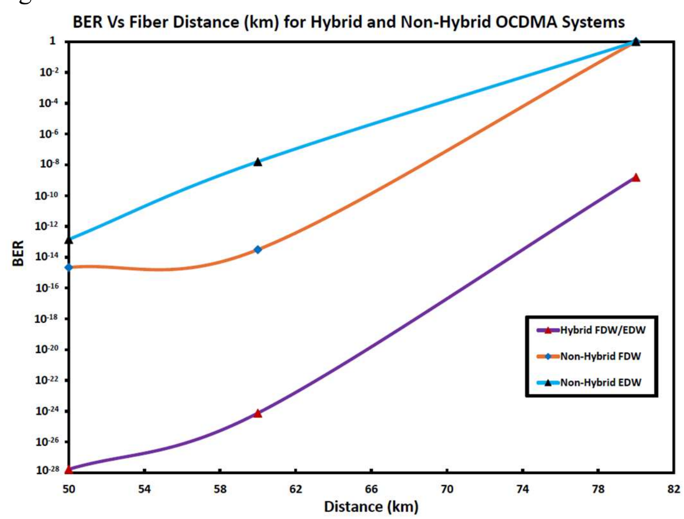


Fig. 8. Graph of BER Against Fiber Distance for Hybrid and Non-Hybrid OCDMA Systems.

Based on the graph in Figure 8, an increase in distance leads to an increase in BER. The hybrid FDW/EDW system has the lowest BER compared to the non-hybrid FDW and EDW systems. This difference indicates the success of the hybrid approach in minimizing errors at greater distances.

VI. CONCLUSION

Hybrid FDW/EDW systems are a combination of 2 distinct OCDMA codes using polarization technique. FDW codes are an enhanced version of Modified Double Weight (MDW) and Enhanced Double Weight (EDW) codes due to their flexibility in code weight and design. EDW code is an odd weighted code which is an improved version of MDW. Polarization encoding is a technique used in the proposed systems to achieve zero cross-correlation properties. The technique utilizes the orthogonal nature of different polarization states to enable multiple users to share the same wavelength thereby improving spectral efficiency and enhancing system security. The combination of two distinct OCDMA codes increases the number of basic code users and supports the reuse of wavelength with different polarity, and the extension of transmission distance. The result shows that Hybrid FDW/EDW has the best BER performance when compared to Non-Hybrid FDW and EDW. Hybrid FDW/EDW can reach up to a transmission distance of 80 km with BER 1.57515 x 10^{-9} compared with Non-Hybrid FDW which can only support 60 km distance with 3.10857 x 10^{-14} BER. The Non-hybrid EDW system on the other hand has the lowest BER performance and transmission distance which is 1.42986 x 10^{-13} for 50 km. Hybrid systems offer up to 60% improvement over non-hybrid systems. The proposed hybrid system is suitable for a combination of any 2 different OCDMA codes such as MDW, EDW, FDW, etc. When simulating and comparing the performance of hybrid OCDMA and non-hybrid OCDMA systems, certain limitations, challenges, and issues may arise. Hybrid OCDMA systems provide greater capacity and spectral efficiency compared to non-hybrid OCDMA systems. However, achieving these advantages often involves trade-offs related to complexity, latency, and vulnerability to noise and channel impairments. Simulation results show that the proposed hybrid scheme significantly enhances signal integrity and scalability in networks when compared to traditional OCDMA systems. This research aids in the advancement of more resilient and efficient optical communication systems for next-generation networks.

AUTHOR CONTRIBUTIONS

S. M. Ammar: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing original—draft preparation, Writing—review and editing. **N. Ali:** Conceptualization, Validation, Resources, Writing—review and editing, Supervision. **M. A. Anuar:** Methodology, Software, Data curation, Writing original—draft preparation, Writing—review and editing. **S. A. Aljunid:** Conceptualization, Software, Validation, Resources, Writing—review and editing, Supervision. **N. M. Saad:** Validation, Resources, Writing—review and editing. **R. Endut:** Validation, Writing—review and editing. **K. S. Manic:** Resources, Writing—review and editing. **I. S. Al Naimi:** Resources, Writing—review and editing. **F. N. Hasoon:** Resources, Writing—review and editing.

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