Performance Improvement of SAC-OCDMA System based on FDW Code using EDFA for Passive Optical Distribution Network (PON)

M. A. Anuar[1, 2*], S. A. Aljunid[1, 2], S. M. Ammar[1, 2], R. Endut[1, 2], N. M. Saad[3], K. S. Manic[4], I. S. Al Naimi[4] and F. N. Hasoon[4]

[1] Faculty of Electronic Engineering and Technology, Universiti Malaysia Perlis, Arau 02600, Perlis, Malaysia
[2] Centre of Excellence Advanced Communication Engineering (ACE), Universiti Malaysia Perlis, Arau 02600, Perlis, Malaysia
[3] Electrical and Electronic Engineering Department, Universiti Teknologi Petronas, Seri Iskandar 32610, Perak, Malaysia
[4] National University of Science and Technology. College of Engineering, Oman

ABSTRACT: This paper investigates the influence of an Erbium Doped Fiber Amplifier (EDFA) on high data rate performance within the Spectral Amplitude Coding Optical Code Division Multiple Access (SAC-OCDMA) networks. The utilization of EDFA in this research aims to mitigate signal attenuation of the system. The proposed system employs Flexible Double Weight (FDW) codes as signature codes, which accommodate four simultaneous users to address noises posed by both phase-induced intensity noise (PIIN) and multiple access interference (MAI). The SAC-OCDMA system's receiver component adopts the structure of Spectral Direct Detection (SDD) technique, known for its zero cross-correlation property, eliminating overlap wavelengths between multiple users and effectively suppressing MAI and PIIN effects. One key advantage of incorporating EDFA is its dual functionality in simultaneous noise suppression and enhancement of signal quality. The synergy between the SDD technique and EDFA is identified as the optimal approach for enhancing the overall performance of SAC-OCDMA access networks. Performance evaluation is based on bit error rate (BER), Q-factor, and received power. Simulation experiments conducted using OptiSystem version 15 demonstrate that employing FDW codes with EDFA yields superior BER results compared to using FDW codes without EDFA. The comparative analysis between SAC-OCDMA systems employing FDW codes with and without EDFA underscores the efficacy of EDFA in enhancing system performance. Furthermore, the capability of the FDW code-based SAC-OCDMA system, coupled with EDFA, to support simultaneous transmissions at varying data rates is successfully demonstrated through simulations, achieving a BER lower than 10^{-9} with four users transmitting at 10 Gbps each. Results indicate that the system with EDFA can successfully transmit signals up to 160 km before experiencing significant distortion, whereas the configuration without EDFA is limited to 80 km. This represents a 100% performance improvement achieved by the SAC-OCDMA system with FDW code through the use of EDFA.

KEYWORDS: OCDMA, FDW, EDFA, SDD, BER.

[Received Oct. 4, 2024; Revised Mar. 2, 2025; Accepted Mar. 9, 2025] Print ISSN: 0189-9546 | Online ISSN: 2437-2110

I. INTRODUCTION

Optical Code Division Multiple Access (OCDMA) represents an approach to efficiently allocate the bandwidth of optical fibre across multiple users within a local area network. Unlike conventional multiplexing methods such as Wavelength Division Multiplexing (WDM) and optical Time Division Multiplexing (TDM), which are more suitable for long-haul networks, OCDMA distinguishes itself by assigning a unique optical code to each user at the transmitter, offering enhanced flexibility and scalability without demanding high-precision wavelength-stabilization techniques or stringent synchronization control. Passive Optical Network (PON) is a telecommunication system that provides services through optical fibre and all the way to end user. PON can support various types of transmission such as audio, im-age, and Video on Demand (VoD). PON consists of Optical Line Unit (OLU), combiner, optical fibre, splitter, and Optical Network Unit (ONU) (Aljunid et al, 2021). Figure 1 shows an illustration of OCDMA-PON system. In an OCDMA-PON system, PON architecture is combined with OCDMA technology to allow multiple users to share the same optical fibre network using unique optical codes. This allows each user to transmit and receive data independently, even though they all use the same physical fibre (Rahat et al, 2024).

OCDMA presents notable advantages for local area network implementations, including support for asynchronous access networks, dynamic bandwidth assignment, all-optical

*Corresponding author: muhammadamirul@studentmail.unimap.edu.my
doi: http://dx.doi.org/1063746/njtd.v22i3.2959

processing, and the facilitation of high-quality multimedia services (Morsy, 2023; Haider et al, 2021; Mohammed et al, 2022) However, the efficacy of OCDMA is constrained by Multiple Access Interference (MAI), arising from simultaneous transmissions by multiple users on a shared channel.

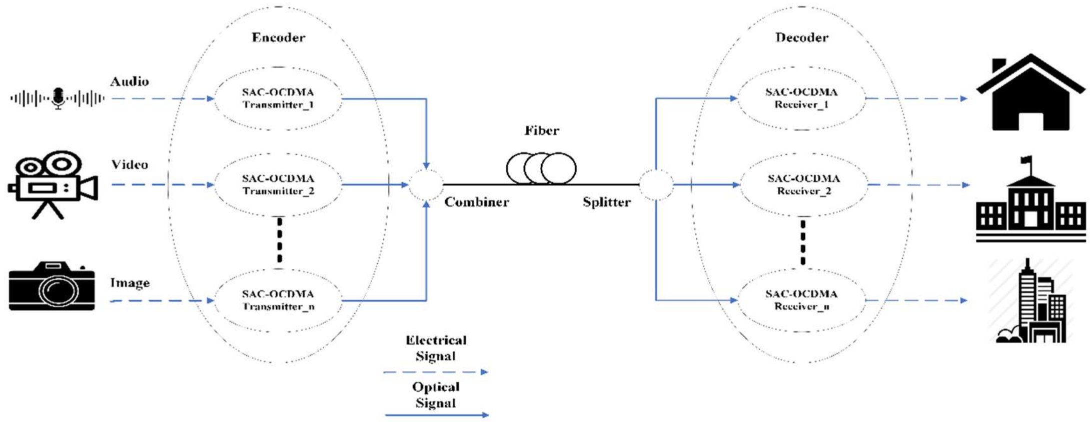


Figure 1. illustration of OCDMA-PON system.

Additionally, inherent to the system design, physical effects introduce various noises, such as Phase Induced Intensity Noise (PIIN), thermal noise, and shot noise. PIIN is particularly linked to MAI, originating from the overlapping wavelengths of different users. Previous studies (Alayedi et al, 2023) underscore the challenge of PIIN resulting from the use of broadband sources, adversely affecting communication quality.

To address these challenges, the Spectral Amplitude Coding OCDMA (SAC-OCDMA) technique has emerged, leveraging spectral coding to completely suppress MAI (Zaccarin and Kavehrad, 1993). Codes employed in SAC-OCDMA systems with intensity detection must exhibit characteristics such as unipolarity, orthogonality (minimized cross-correlation), and a constant weight value to achieve a low probability of error attributed to MAI (Harshavardhana et al, 2022). Several codes have been proposed in the literature for SAC-OCDMA networks, including the modified frequency-hopping (MFH) code (Mohamed et al, 2022), optical orthogonal code (OOC) (Chauhan et al, 2020), and modified quadratic congruence (MQC) code (Das and Jahedul Islam, 2022). However, limitations in code length and construction parameters exist, and certain codes may not support a substantial number of simultaneous users or high data rates.

SAC-OCDMA codes from the DW code family which are the Modified Double Weight (MDW), and Enhanced Double Weight (EDW) codes were proposed initially. However, each of these codes exhibit inherent limitations and performance drawbacks when applied in practical OCDMA networks. These codes were primarily developed to mitigate crosstalk and minimize multiple access interference (MAI), but their effectiveness is often constrained by factors such as limited code length flexibility, reduced cardinality, or increased system complexity. Addressing these constraints, a new code from the DW code family known as Flexible Double Weight (FDW) codes (Ammar et al, 2023) has been introduced, characterized by zero cross-correlation, ideal for accommodating a large number of users and high data rates.

The primary goal of this study is to incorporate EDFA (Erbium-Doped Fiber Amplifier) into a SAC-OCDMA system employing an innovative code from the DW family known as the FDW code. EDFA is added to boost the optical signal across the network, especially to compensate for losses introduced by passive splitters in the PON. EDFA ensures that the system can support longer transmission distances and more users while maintaining acceptable signal quality (Makwana et al, 2024). The FDW code incorporates a novel polarization encoding method to address challenges encountered in prior systems.

The design of the FDW code is notably simpler in comparison to Hadamard, MFH, MDW, and EDW codes. FDW code features a reduced code length, and its weight can be either odd (as in EDW) or even (as in MDW). The application of the polarization encoding technique compresses the code, enabling support for a greater number of users with a shorter code length. Based on the fundamental principles of light polarization, a novel encoding system has been formulated. Light, as a transverse electromagnetic wave, exhibits electric and magnetic field oscillations perpendicular to each other and in any plane orthogonal to the light's direction of motion. A unique method employing the FDW code is applied to achieve zero cross-correlation properties within the same wavelength. This distinguishes it from other codes in the DW family.

The application of EDFA in OCDMA systems provides high-gain, low-noise amplification in the 1550 nm wavelength range, which matches the low-loss window of optical fibres. This allows long-distance transmission in OCDMA networks without requiring frequent electronic regeneration. EDFA also supports simultaneous amplification of multiple users' signals, which is essential in OCDMA where many signals share the same fibre. This enhances system scalability and improves receiver sensitivity. Compared to other amplifiers, EDFA's broadband gain allows it to handle the broad spectral width of OCDMA signals efficiently, enabling higher data rates and better multi-user support. These advantages make EDFA a key enabler for practical, high-capacity OCDMA systems. Paired with the polarization technique based on the FDW code, the system is expected to achieve a high transmission rate in a long-haul system (Horvath et al, 2020).

Various detection techniques have been proposed for SAC-OCDMA systems, including logic gates simulating logical multiplication operations such as logical AND subtraction (Islam et al, 2024), modified AND subtraction (Abd El-Mottaleb et al, 2018; Sharma et al 2022), and complementary subtraction (Thakur et al, 2020). Notably, the Spectral Direct Detection (SDD) technique, established in (Alayedi et al, 2022), has demonstrated efficacy in ultra-high-speed transmission, noise suppression, and cost-effectiveness. Building upon prior research presented in (Abdulqader et al, 2014), Erbium Doped Fiber Amplifiers (EDFAs) operating in gain saturation have been explored as a means to suppress optical intensity noise, previously proposed for use in WDM systems. The EDFA's capability for simultaneous noise suppression and signal quality improvement presents a compact solution for access markets. Extensive research and investigation have been conducted on this method to suppress channel noise in SDD detection and enhance overall system performance in terms of bit-error rate (BER). Moreover, the impact of incorporating an erbium-doped fibre amplifier (EDFA) on system performance has been thoroughly examined. All simulations were meticulously executed using OptiSystem version 15.

II. FLEXIBLE DOUBLE WEIGHT (FDW) CODE (METHODOLOGY I)

The FDW code presents a significant advancement compared to the DW (Aljunid et al, 2004), MDW (Kumar and Ahuja, 2021), and EDW codes (Sarangal et al, 2019), providing increased flexibility in terms of code weight. Unlike its predecessors, the FDW code accommodates both odd weights, as seen in the case of EDW, and even weight, similar to MDW, in terms of code weights. The FDW sequence closely mirrors that of DW, but with notable enhancements which feature a code sequence of 1, 2, 1, ..., 1n (Ammar et al, 2023). A distinctive attribute of FDW is its fixed fundamental user code, consistently set at 2 which deviates from prior OCDMA codes where each weight had a distinct fundamental user code.

Table 1. FDW Code with Weight (W) of 3

W=3	**A**		**B**		**C**		**D**		**E**		
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	3
2	0	0	0	0	0	1	0	1	1	0	3
3	0	1	0	1	1	0	0	0	0	0	3
4	1	0	1	1	0	0	0	0	0	0	3
-	-	-	-	-	-	-	-	-	-	-	-
-	1	1	1	2	1	1	1	1	2	1	-

Table 2. FDW Code with Weight (W) of 4

W=4	**A**		**B**		**C**		**D**		**E**		**F**		**G**		
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	1	-

Tables 1 and 2 depict the fundamental code structure of FDW which highlights the arrangements for odd (W = 3) and even (W = 4) code weights. This design decision emphasizes the versatility of the FDW code in accommodating both odd and even weight scenarios, offering a comprehensive framework suitable for diverse applications. The code sequences presented in Tables 1 and 2 demonstrate a cross-correlation (λc) of 1, coupled with a high autocorrelation (λa). The interconnection among the variables K, N, and W is briefly described through the general formula provided hereafter. Furthermore, the observed cross-correlation of one in the given code sequences signifies a strong linear relationship between them. Equation 1 shows the codelength for the FDW code.

The utilization of the FDW code entails in exploiting its inherent characteristics within an identical wavelength to attain a state of zero cross-correlation to introduce a new innovative approach in mitigating MAI. In contrast to alternative codes within the DW category, FDW distinguishes itself to be exceptionally capable for use in Local Area Networks (LANs) (Ghazi et al, 2021), providing the potential to facilitate high bit rates. This distinctive positioning renders FDW code a notable selection in situations where both zero cross-correlation and high bit rates hold a significance, underscoring its adaptability and relevance across diverse communication system environments.

III. SDD TECHNIQUE IMPLEMENTATION WITH EDFA (METHODOLOGY II)

In using the Spectral direct detection (SDD) technique, the receiver only needs a single decoder input, unlike other techniques that require two decoder parts. The use of Direct detection technique reduces the number of filters needed at the receiver and eliminates the subtraction process. This is possible because the information can be adequately recovered from individual chips that do not overlap with chips from other code sequences.

Therefore, the decoder only needs to filter through the non-overlapping chips to detect them directly using the photodiode. This technique is suitable for codes designed with zero cross-correlation, which completely eliminates the MAI and PIIN effects, thus improving the system's BER. When multiple users are present, the variation in chip power can negatively affect system performance. However, this issue can be resolved by using zero cross-correlation codes. In this evaluation of the system's BER, shot noise and thermal noise are considered, assuming that the PIIN effects are completely eliminated (Ammar et al, 2025). Figure 2 shows a standard SDD technique receiver configuration for the OCDMA system. User 1's code sequence (X) is represented as 0110 (0 λ2 λ3 0), while User 2's code sequence (Y) is 1100 (λ1 λ2 0 0).

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

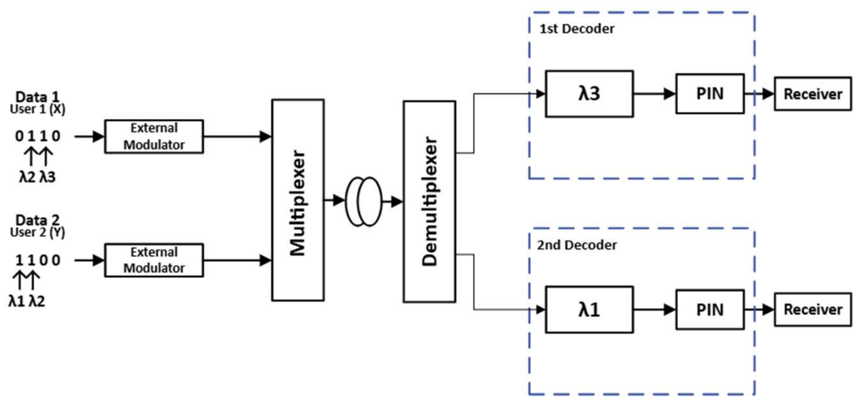
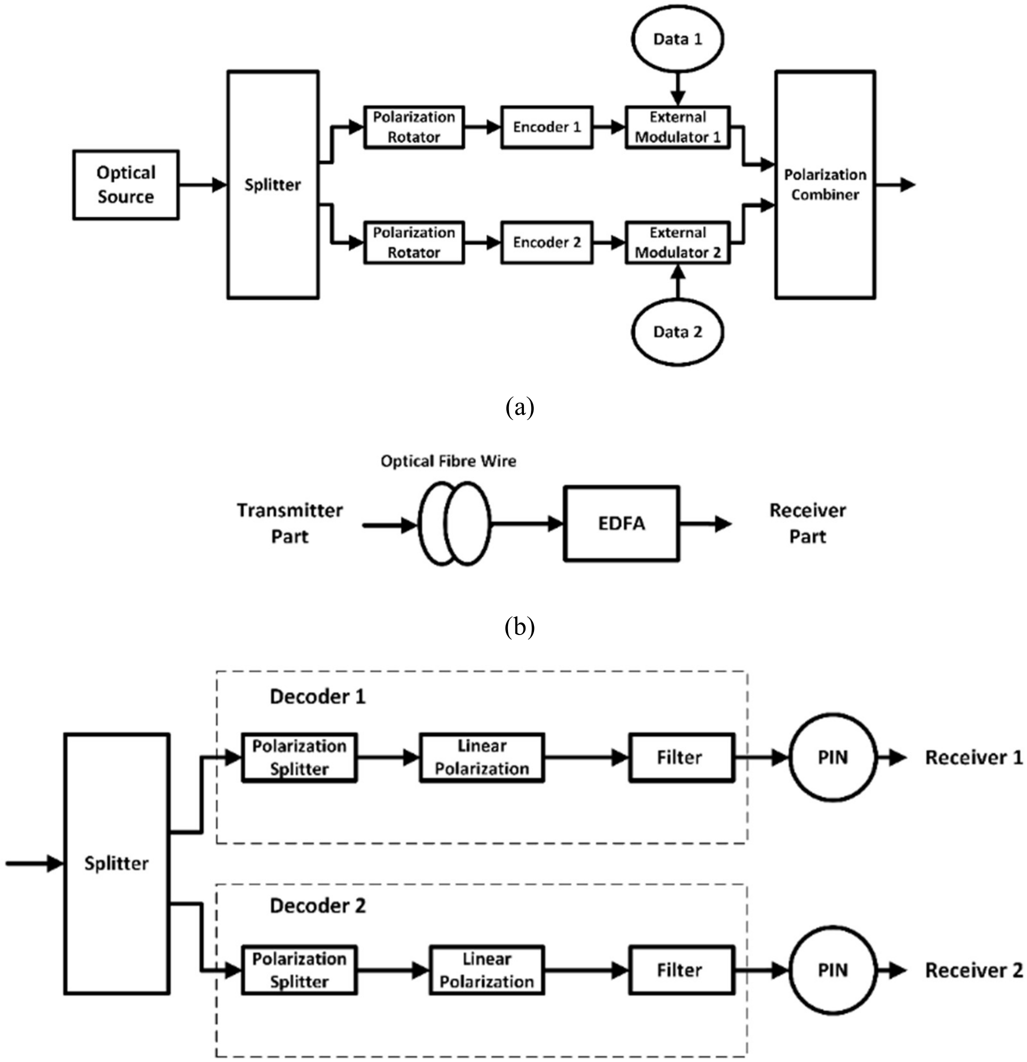


Figure 2. OCDMA SDD Technique

These two codes share an interference chip, which is represented by 'λ2'. The Spectral Direct detection technique involves directly detecting the signal from a clean, non-overlapping chip which are 'λ1' and 'λ3'. As a result, the decoder will only have to filter through the uncontaminated signals within the data segment. These signals are directly detected by a photodiode, following the SDD technique.

The principal material employed for the long-haul telecommunication applications is a silica fibre infused with erbium, recognized as an erbium-doped fibre amplifier (EDFA) (Facchini et al, 2023). Initially, the functionality of a standalone EDFA was confined to the c-band, spanning the 1530nm to 1560nm range, owing to the heightened gain coefficient of erbium atoms within this spectrum. This characteristic serves as the basis for labelling it as the conventional band or C-band in the system conducted in this research. Beyond this range, the erbium gain peak diminishes rapidly, dwindling to only 20% of that in the C-band within the Lower band(L-band) (Sachdeva et al, 2022). Figure 3 illustrates the configuration of the proof-of-principle simulation for the FDW code SAC-OCDMA system with EDFA, where each wavelength exhibits a spectral width of 0.8 nm. The conducted tests operated at a 10 Gbps rate utilizing a standard single-mode fibre (SMF).



(c)

Figure 3. OCDMA system with FDW Code Setup (a) Transmitter Part (b) Channel with EDFA (c) Receiver Part

The EDFA is positioned directly preceding the SDD technique receiver part, functioning as an "in-line amplifier." This in-line amplifier needs to exhibit high gain and minimal noise to preserve the signal-to-noise ratio of a previously attenuated signal without degradation. Implementing the SDD technique into the FDW code is deemed the simplest and most straightforward approach compared to other detection techniques that involve intricate implementation processes. This technique is the only technique that directly chooses the desired signal without any arithmetic process.

The system's operational efficiency is evaluated by assessing the BER. Subsequent to the signal processing within the SDD receiver part, the decoded signals underwent detection via a photodetector (PD). Positioned before the receiver part, the EDFA served as an in-line amplifier. The primary requirement for this in-line amplifier was to exhibit substantial gain while maintaining minimal noise, thereby preserving the signal-to-noise ratio of a signal that had already undergone attenuation.

The simulation design setup of the FDW code system comprises an encoding system with the transmission medium (transmitter part) and the decoding system with data recovery (receiver part). Also to note, a broad-spectrum LED serves as the optical source, with an 8nm bandwidth, while the WDM demultiplexer and multiplexer are responsible for encoding the wavelength domain, using a chip width of 0.8 nm. Figure 4 shows the simulation setup of FDW code system with EDFA.

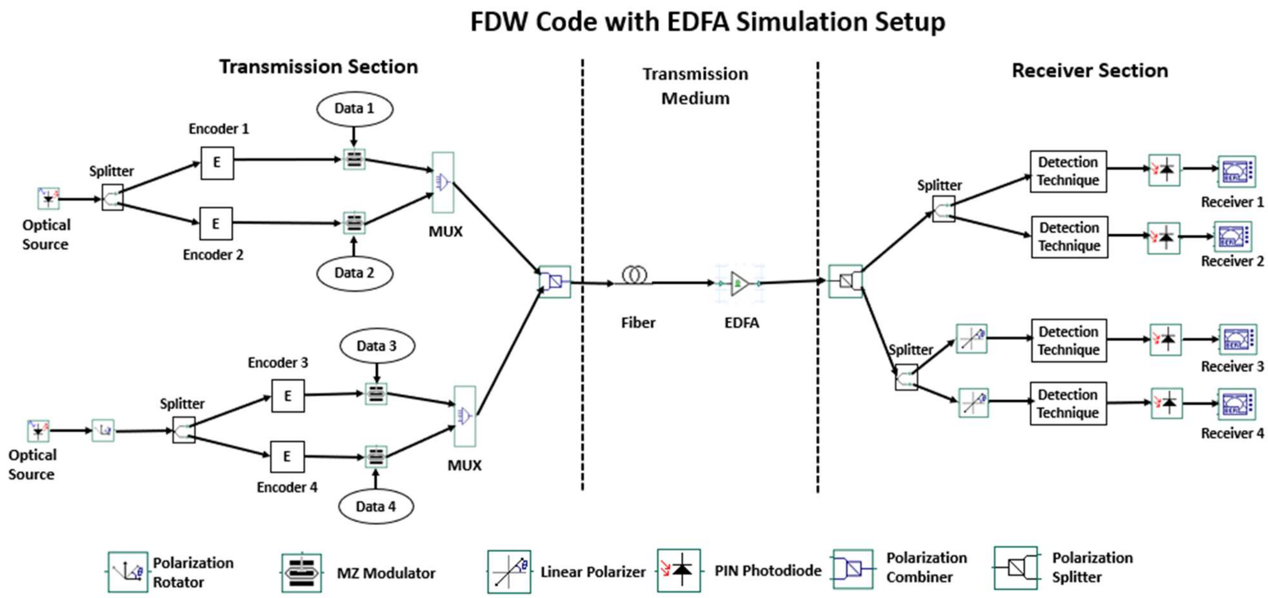


Fig. 4. Simulation setup of FDW code system with EDFA

Based on Figure 4, for the Transmitter part, the generation of random data with a pattern length of 2^7 - 1 is achieved using a Pseudo Random Bit Sequence (PRBS) generator, while the Non-Return-to-Zero (NRZ) pulse generator converts the PRBS signal into an NRZ electrical signal. The Mach-Zehnder Modulator (MZM) modulates the three multiplexed wavelengths from the Wavelength Division Multiplexer (WDM). The encoded signal wavelength of all users will be transmitted through the single-mode fibre (SMF) at 1550 nm where the EDFA is applied.

The receiver part is where the decoding process is done using the SDD technique. From Figure 4, the signal that arrived from the fibre optic is split into each decoder, which represents channels for each individual user. After going through the filtering process, the channel signals are converted to electrical signals through the photodiodes. For data recovery, the Bessel Filter filters the electrical signal from the photodiode, which can be analysed using a BER analyser.

IV. PERFORMANCE ANALYSIS

To determine the performance of OCDMA systems, OptiSystem 15 was used to simulate and analyse the BER obtained at the receiver. The Bit Error Rate (BER) and transmission distance is the basis of comparison between FDW systems with EDFA and without EDFA. The BER must be less than 10^{-9} for the system to work properly. The BER is a key performance metric used to quantify the number of bit errors in a transmission over a communication channel. It is defined as the ratio of the number of incorrect bits received (errors) to the total number of bits transmitted during a given period. Mathematically, it is expressed as:

$$BER = \frac{Number\ of\ bit\ errors}{Total\ number\ of\ bits\ transmitted} \quad (2)$$

Signal-to-noise ratio (SNR) measures system and signal quality. Table 3 shows the parameter used in OCDMA systems.

Table 3. Parameters for OCDMA systems

Parameters	Unit
Photodetector quantum efficiency (ɳ)	0.6
Operating wavelength (λo)	1550 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 Resistor (R_L)	1030 Ohm
Bit Rate	10 Gbps
EDFA Gain	20 dB
EDFA Length	5m

The evaluation of telecommunication system transmission quality involves a direct measurement of how accurately the output signal replicates the input. In digital communication systems, the concept of Bit Error Rate (BER) is employed to assess signal quality. A Bit Error Rate of not more than 10^{-9} is commonly considered acceptable for telecommunications transmission. Thus, lower BER accommodates better transmission quality.

The Q-factor offers a qualitative characterization of receiver performance as it is dependent on the optical signal-to-noise ratio. It indicates the minimum SNR needed to achieve a particular Bit Error Rate (BER) for a given signal. The received optical power signifies the initial optical power emitted by the light source upon reaching the receiving end of the optical module. It stands as a significant parameter influencing the transmission distance of the signal.

V. RESULTS AND DISCUSSIONS

Figure 5 shows the eye pattern for the FDW system without using EDFA at 80 km with a 10 Gbps bit rate. The maximum range for FDW systems is within 80 km before the quality of the signal starts to drop above the acceptable BER value. Beyond this distance, the signal quality drops, meaning the BER exceeds the acceptable limit, which is around 10^{-9} to the optical communication systems. This degradation occurs due to the signal becoming too weak and distorted for the receiver to correctly decode the transmitted data.

The eye pattern helps evaluate how clear and distinguishable the transmitted bits are after traveling through the fibre. A wide-open eye indicates good signal quality which means the receiver can easily distinguish between logical ‘1’ and ‘0’. However, at longer distances, the signal experiences attenuation and dispersion, causing the eye to close and the BER to increase. To extend the transmission range, EDFA is applied to FDW system shown in Figure 6.

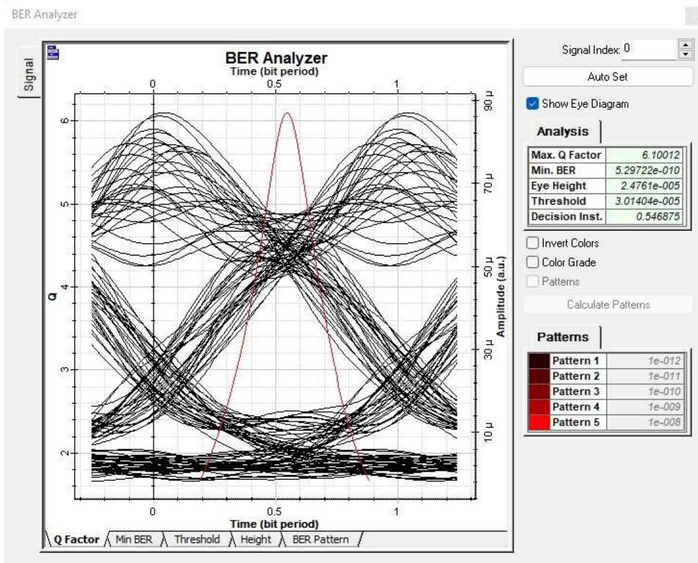


Fig. 5. Eye Pattern for FDW System Without Using EDFA At 80 km with 10 Gbps Bit Rate.

The transmission range is doubled when applying EDFA which travels up to 160 km. As signals travel over long distances in optical fibres, they experience power loss, which can severely degrade the SNR, specifically in PONs where the signal is split among multiple users. The transmission range can be doubled with the application of EDFA where it provides optical signal amplification directly in the fibre which reduces the need for electrical regeneration. By amplifying the signal optically, EDFA compensates for fibre attenuation, allowing the signal to travel much farther before becoming too weak or distorted. This improvement shows the ability of the FDW system with EDFA to perform in long haul network applications.

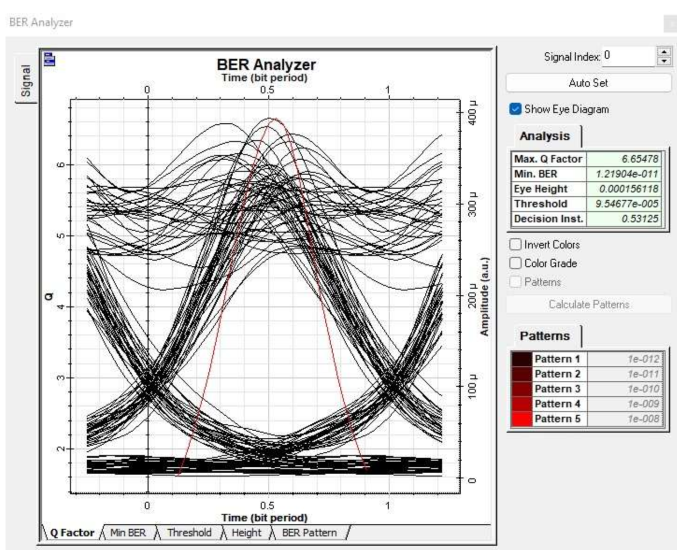


Fig. 6. Eye Pattern for FDW System Using EDFA at 160 km with 10 Gbps Bit Rate.

For further analysis, FDW system BER results consist of 4 channels and were tabulated in Table 4. Table 4 contains the BER results for every channel at specific transmission distance. The analysis is based on FDW using EDFA and without EDFA.

According to the simulation results in Table 4, the BER for all channels is stable. The fibre length was doubled when FDW used EDFA as optical amplifier. FDW with EDFA are suitable for high-speed communication systems and compensate for the trans-mission loss within optical fibre. In the simulated FDW code SAC-OCDMA system with four channels, the difference in BER reduction across channels can be explained by variations in code properties and interference levels.

Even in a simulation, small power variations across wavelengths or differences in noise contributions to each channel can lead to unequal BER performance. These combined effects explain why the BER improvement is not uniform across all channels, even under ideal simulation conditions.

Table 4. Comparison of FDW system performance using EDFA and without EDFA for 4 channels with 10 Gbps bit rate.

OCDMA Codes	Fiber Length (km)	Channels	Bit Error Rate (BER)
FDW Without EDFA	80	1	5.29722×10^{-10}
		2	3.69845×10^{-10}
		3	1.58314×10^{-11}
		4	1.22017×10^{-9}
	70	1	3.35592×10^{-16}
		2	4.49118×10^{-16}
		3	8.20136×10^{-17}
		4	2.14813×10^{-14}
FDW Using EDFA	160	1	1.21904×10^{-11}
		2	9.47424×10^{-10}
		3	7.96044×10^{-12}
		4	2.26878×10^{-13}
	140	1	5.49162×10^{-16}
		2	7.76304×10^{-17}
		3	2.96909×10^{-17}
		4	1.71833×10^{-16}

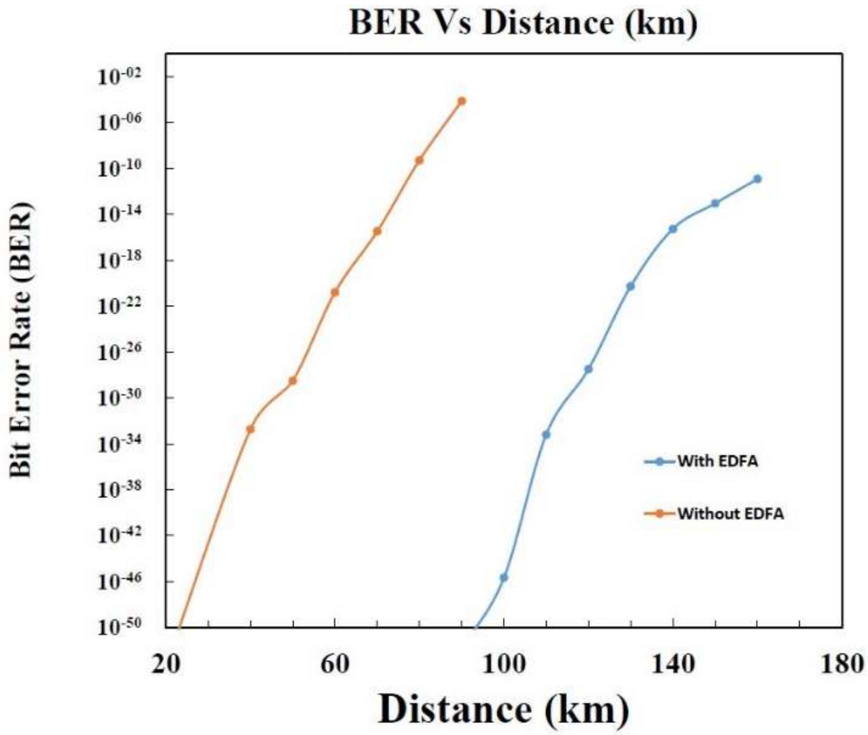


Fig. 7. BER vs Distance

The plotted graph in Figure 7 shows the system's performance in terms of BER. The FDW code SAC-OCDMA system with EDFA is able to transmit up to 160km before the signal becomes fully distorted whereas the system without EDFA can reach up to 80km with minimum acceptable BER. This represents a 100% performance improvement achieved by the SAC-OCDMA system with FDW code through the use of EDFA. Therefore, it shows that the system with EDFA can perform better in long-haul communication systems.

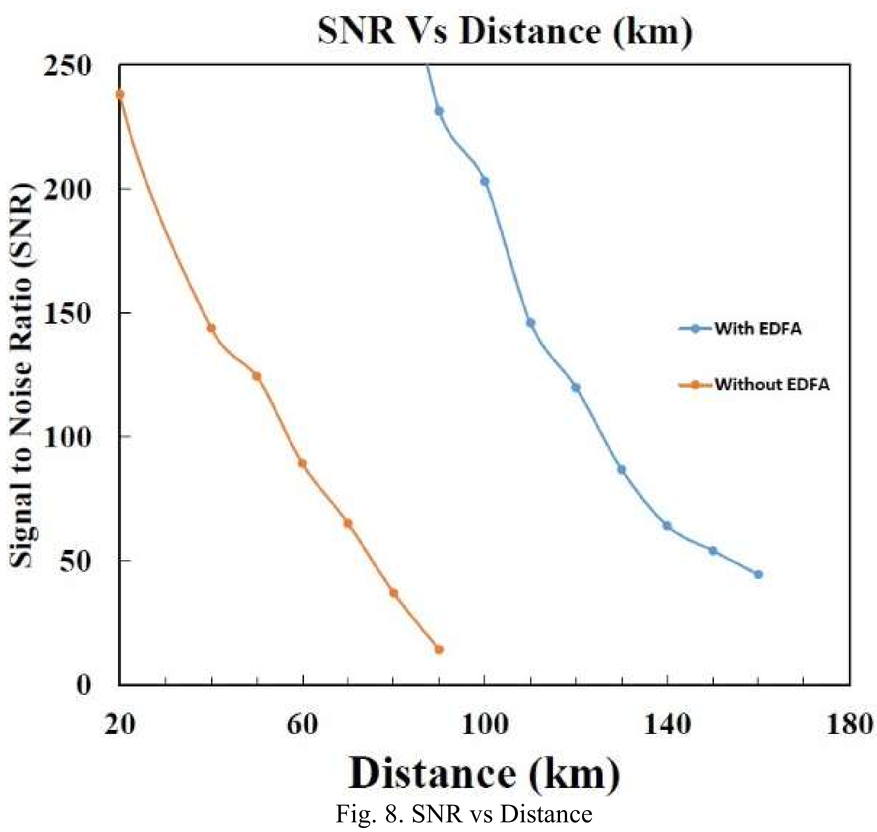


Fig. 8. SNR vs Distance

The plotted graph in Figure 8 shows the system's performance in terms of SNR. The FDW code SAC-OCDMA system with EDFA has higher SNR at longer distance in comparison to the system without EDFA. Higher SNR means that a better quality of signal can be achieved. Thus, this shows that the system with EDFA has better signal quality than the system without EDFA. A more detailed SNR comparison is shown in Table 5.

Table 5. SNR comparison of FDW code with and without EDFA

Km	SNR Value	
	FDW code without EDFA	**FDW code with EDFA**
160	0	44
150	0	54
140	0	64
130	0	86
120	0	119
110	0	146
100	0	203
90	14	231
80	37	314
70	65	377
60	89	496
50	124	-
40	143	-
30	191	-
20	238	-
10	384	-

VI. CONCLUSION

The OCDMA system is one of the multiple access schemes that utilize codes for data transmission. Passive Optical Networks (PON) with OCDMA provide dedicated codes for each Optical Network Unit (ONU). FDW is one of the OCDMA codes categorized as a DW family code. The code weight for FDW is flexible, providing an alternative to design odd- or even-weighted codes. FDW uses polarization as its encoding and decoding technique. The polarization technique can reuse the spectrum with different polarities to compact the FDW code. EDFA was introduced to amplify the optical signal, extending the transmission distance and compensating for transmission and loss of optical splitters. The results from this study show that an FDW system using EDFA can extend the transmission distance from 80 km (without EDFA) to 160 km, effectively doubling the distance before surpassing the acceptable BER of 10^{-9}. The simulation results further confirm that integrating EDFA improves system performance by significantly enhancing received power and maintaining a low BER over an extended range. EDFAs, widely utilized in telecommunications, serve as the predominant type of optical amplifier in optical communications and networking. Their application is crucial in overcoming signal attenuation, particularly in long-distance communication. Placing amplifiers at regular intervals along the transmission line enhances the optical signal, facilitating extended travel without significant degradation. The findings of this study reinforce the critical role of EDFA in enabling high-speed, long-haul optical networks, particularly in SAC-OCDMA systems where maintaining signal integrity is crucial. The ongoing demand for higher data rates and extended transmission distances underscores the growing significance of optical amplifiers in communication infrastructure. Researchers are persistently working to enhance optical amplifier performance, focusing on reducing noise figures, amplifying gain, and broadening the operational wavelength range. FDW using EDFA in OCDMA-PON is capable of providing long-haul network service and wide area networks (WANs). Overall, while EDFA offers critical performance improvement in terms of transmission range and power budget, its integration into FDW-based SAC-OCDMA requires careful optical design, noise management strategies, and code preservation techniques to ensure reliable operation. The findings of this research highlight the potential of FDW-coded SAC-OCDMA systems with EDFA as a practical solution for future high-speed optical networks.

AUTHOR CONTRIBUTIONS

Conceptualization, **M. A. Anuar., S. A. Aljunid. and R. Endut.**; Methodology, **M. A. Anuar and S. M. Aljunid.**; Software, **M. A. Anuar., S. M. Aljunid. and S. A. Ammar.**; Validation, **R. Endut., N. M. Saad. and S. A. Aljunid.**; Formal analysis, **M. A. Anuar.**; Investigation, **M. A. Anuar.**; Resources **S. A. Aljunid., N. M. Saad., K. S. Manic., I. S. Al Naimi and F. N. Hasoon.**; Data curation, **M. A. Anuar. and S. M. Ammar.**; Writing original—draft preparation, **M. A. Anuar., and S. M. Ammar.**; Writing—review and editing, **M. A. Anuar., S. M. Ammar, R. Endut., S. A. Aljunid., N. M. Saad., K. S. Manic., I. S. Al Naimi and F. N. Hasoon.**; Supervision, **S. A. Aljunid.** All authors have read and agreed to the published version of the manuscript.

ACKNOWLEDGEMENT(S)

This research has been carried out under LRGS Grant LRGS/1/2020/UM/01/5/4 (9012-00010) Integration of Optical Code Division Multiple Access utilizing Quan-tum Key Distribution for Secure Quantum Communication Network provided by the Ministry of Higher Education of Malaysia (MOHE).

REFERENCES

Abd El-Mottaleb S. A., Fayed H. A., Abd El-Aziz A., Metawee M. A., and Aly M. H. (2018). Enhanced Spectral Amplitude Coding OCDMA System Utilizing a Single Photodiode Detection. Applied Sciences, 8(10), 1861

Abdulqader, S. G., Aljunid S. A., Al-Khafaji, H. M. R. and Fadhil, H. A. (2014). Enhanced Performance of SAC-OCDMA System based on SPD Detection Utilizing EDFA for Access Networks. Journal of Communications 9(2), 99-106.

Alayedi, M., Abdelhamid, C., Abdelhak Ferhat, A., Mrabet, H. (2022). A fair comparison of SAC-OCDMA system configurations based on two-dimensional cyclic shift code and spectral direct detection. Telecommunication Systems 79(1).

Alayedi, M., Cherifi, A., Hamida, A.F., Matem, R., Abd El-Mottaleb, S.A. (2023). Performance improvement of SAC-OCDMA network utilizing an identity column shifting matrix (ICSM) code. Advances in Cybersecurity, Cybercrimes, and Smart Emerging Technologies, CCSET, 4.

Aljunid S. A., Zuraidah Zan, Barirah, S. A. A., Anas, A. and Abdullah, M. K. (2004). A New Code for Optical Code Division Multiple Access Systems. Malaysian Journal of Computer Science 17(2), 30-39.

Aljunid, S. M. A., Anuar, M. A., Ismail, A. A. M., Keraf, N. D., Matem, R., Rashidi, C. B. M., Ali, N., Amirul, M. S., Endut, R., Hambali, N. A. M. A., and Aljunid, S. A. (2021). Two Dimensional (2D) OCDMA Encoder/Decoder for Various Industrial Application. International Journal of Nanoelectronics and Materials 14, 175-182.

Ammar S. M., Ali N., Saad M. N., Aljunid S. A., Endut R., Alhassan A. M., Edet C. O. (2023). Development of New Spectral Amplitude Coding OCDMA Code by Using Polarization Encoding Technique. Applied Sciences 13(5), 2829.

Ammar, S. M., Anuar, M. A., Ali, N., Saad, M. N., Syed Alwee Aljunid, S. A., Endut, R., and Al-Khafaji, H. M. (2025). Performance Analysis of Various Detection Techniques in SAC-OCDMA with NRZ and RZ Line Coding. Journal of Advanced Research in Applied Sciences and Engineering Technology 1.

Chauhan, R. C. S., Kumar, A. and Gautam, P. R. (2020). Optical orthogonal code generation scheme and grouping of codes for optical CDMA systems. International Journal of Systems Assurance Engineering and Management, 12, 91–103.

Das, M. and Jahedul Islam, Md. (2022). Performance of MQC Code-Based SAC-OCDMA in FSO System. Innovations in Electronics and Communication Engineering, 13-20.

Facchini, A., Morana, A., Mescia, L., Campanella, C., Shuvo, M. M. K., Robin, T., Marin, E., Ouerdane, Y., Boukenter, A., Girard, S. (2023). Experimental–Simulation Analysis of a Radiation Tolerant Erbium-Doped Fiber Amplifier for Space Applications. Applied Sciences, 13(20), 11589.

Ghazi, A., Aljunid, S. A., Idrusi, S. Z. S., Fareed, A., Hamood, L., Endut, R., Ali, N., Rashidi, C. B. M., Fakhrudeen, A. M., Al-Dawood, A., Matem, R., and Abdullah, S. S. (2021). Comparison of MD & ZCC One Dimension Code for Optical-CDMA over Multi-mode Fiber based on Laguerre-gaussian modes. Journal of Engineering Science and Technology, 16(4), 3588 – 3599.

Haider, J. Abd., Mohammed, T. G., Hanaa, Al., Sukainaalbairmani, and Muthanna, J. A. (2021). Coherent Optical Code Division Multiple Access for FTTH Network: Review Paper. Journal for Advanced Research in Applied Sciences, VIII, 1-8.

Harshavardhana, M. N., and Suraiya, T. (2022). Performance analysis of optical spectral amplitude CDMA system unipolar codes with double weight construction design. Journal of Optical Communications, 46(1), 27-39.

Horvath, T., Radil, J., Munster, P, and Bao, N-H. (2020). Optical Amplifiers for Access and Passive Optical Networks: A Tutorial. Applied Sciences, 10(17), 5912.

Islam, F., and Uddin, M. N. (2024). Empirical Analysis of the SAC-OCDMAWDM System by Leveraging the AND Subtraction Technique. AIUB Journal of Science and Engineering, 23(2), 145 - 157.

Kumar, S. and Ahuja, B. (2021). Performance of EDW and MDW codes in spectral amplitude coded OCDMA system with SPD. Optical and Quantum Electronics 53(11).

Makwana, M., Khant, S., and Patel, A. (2024). Advancements in Long-Distance PON Connectivity using WDM and EDFA. 11th International Conference on Reliability, Infocom Technologies and Optimization (Trends and Future Directions) (ICRITO), Noida, India, 1-6.

Mohamed I. M. M. and Abdulrahman, O. M. (2022). SAC-based OCDMA codes: A comparison. ELEKTRIKA Journal of Electrical Engineering 21(1), 20-24.

Mohammed, H. A., Abu Bakar, M. H., Anas, S. B. A., Mahdi, M. A., and Yaacob, M. H. (2022). Optical fiber sensor network integrating SAC-OCDMA and cladding modified optical fiber sensors coated with nanomaterial, Optical Fiber Technology 70, 102875,

Morsy, M. A. (2023). Coherent OCDMA network based on a new BER performance equalization technique for multimedia applications. Optical and Quantum Electronics 55(167).

Rahat, U., Sibghat, U., Waqas, A. I., Abdullah, A. A., Zaid, A., and Hathal, S. A. (2024). Optimization and analysis of Spectral/Spatial optical code division multiple access passive optical network. International Journal of Electronics and Communications, 175, 155084.

Sachdeva, S., Pahuja, H., Sindhwani, M. and Arora, K. (2022). A reach enhanced hybrid OCDMA-MDM multiplexing based IsOWC system incorporating EDFA, SOA, and RFA. Journal of Optical Communications.

Sarangal, H., Singh, A., and Malhotra, J. (2019). Construction and Analysis of a Novel SAC-OCDMA System with EDW Coding using Direct Detection Technique. Journal of Optical Communications, 40, 2019, 265-271.

Sharma, T., and Ravi Kumar, M. (2022). Analytical Comparison of Various Detection Techniques for SAC-based OCDMA Systems: A Comparative Review. Optical and Wireless Technologies. Lecture Notes in Electrical Engineering, 771. 63-67.

Thakur, S., and Shahi, A. (2020). Performance Improvement of OCDMA System with Single Photodiode Detection Technique. Proceedings of the International Conference on Innovative Computing & Communications (ICICC) 2020.

Zaccarin, D. and Kavehrad, M. (1993). An optical CDMA system based on spectral encoding of LED. IEEE Photonics Technology Letters 5(4), 479-482.