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# Review of Compensation and Dispersion Techniques for Fiber Optic Lightpath Networks

**Sudha Sakthivel[1], Muhammad Mansoor Alam[2], Aznida Abu Bakar Sajak[3], Mazliham Mohd Suúd[4] and Mohammad Riyaz Belgaum[5]**

[1,3]*Malaysian Institute of Information Technology (MIIT), Universiti Kuala Lumpur, Kuala Lumpur 50250, Malaysia*
[1]*University of Technology and Applied Sciences, Muscat, Oman*
[2]*Faculty of Computing, Riphah International University, Islamabad, Pakistan*
[4]*Malaysian France Institute (MFI), Universiti Kuala Lumpur 50250, Malaysia*
[5]*G. Pullaiah College of Engineering and Technology. Kurnool, INDIA*
[2,4,5]*Multimedia University, Cyberjaya, Malaysia*

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**Abstract:** Fiber optic communication system offers high-speed, long-distance connectivity and integrates with effective data transmission for modern world applications. The primary challenges in optical communication lead to the detrimental impact of dispersion, which introduces more signal distortion and lowers the quality of data transmission. This research aim is to enhance the performance and reliability of the optical system design by addressing dispersion challenges. This review explores the fundamental analysis of dispersion, such as chromatic, polarization mode, and modal dispersion, and the factors that influence the presence of dispersion characteristics. This research also provides a detailed analysis of dispersion compensation techniques and their necessity for maintaining the integrity of optical communication. Furthermore, the proposed review analyses the passive and active compensation techniques and highlights their significance and limitations. Active dispersion compensation, such as dispersion compensating modules and Digital signal processing methods, are investigated for dynamic optical networks and their adaptability. However, the passive dispersion compensation techniques, such as fiber Bragg gratings and dispersion-compensating fibers, are examined in detail, listing their ability for dispersion mitigation effects. Finally, this comprehensive review provides key insights into the developments and prospects in dispersion compensation techniques

**Keywords:** optical communication, dispersion, compensation, Feedforward Equalizer, performance metrics.

## 1. INTRODUCTION

The COVID-19 pandemic has increased the demand for broadband services, highlighting the importance of fiber optic communication systems in delivering high-speed and long-distance connectivity. This leads to understanding the various optical lightpath and their working principles to meet the requirement of huge bandwidth applications. However, these systems face significant challenges, such as dispersion, which leads to signal distortion and limiting data transmission quality. Wavelength division multiplexed lightpaths connection enables faster and higher bandwidth network communication [1]. However, the light path design model involves challenges like nonlinear issues, dispersion effects, and other fiber losses. In long-haul lightpath communication, the effects of the challenges, as mentioned earlier, will arise over the fiber's length [2]. Amplifiers can be utilized in the lightpath system to overcome the losses, but the problems of nonlinear effects and dispersion are adverse. These issues can challenge the quality of data transmission in fiber optic lightpaths and suppress the performance of the system [3].

Fig. 1 shows the basic optical link diagram for the lightpath networks. In Lightpath Communications, data is transmitted in the form of photons. EM waves are used to modulate light information. These waves are used as carrier signals with the help of optical fiber communication large bandwidth [4]. Variations in the performance of Optical Fiber Communication are seen due to many factors, such as scattering, bending loss, absorption, and other nonlinear effects. In Fiber with Single Mode, Polarization Mode and Chromatic Dispersion are the major limiting factors [5]. Light pulse, which carries information that spreads in the fiber output, leads to signal dispersion. Recent developments involve a combination with EDFA, which allows the transmission of light signals over a long distance with reduced cost and increased flexibility [6]. Penalties can accumulate over the entire system. Distributed feedback

*E-mail address: sudha.sakthivel@s.unikl.edu.my, m.mansoor@riphah.edu.pk, aznida@unikl.edu.my, mazliham@mmu.edu.my, riyaz@gpcet.ac.in*

laser has an operating wavelength of around 1.3um in a wide telecommunication window with a bandwidth of 1.55 um. Different modes of light pulse or wavelengths in fiber optics transmit at different rates. These models are received in the fiber terminal at different times. This will lead to colossal distortion, resulting in many errors [7].

Dispersion and nonlinear issues are the significant obstacles to enhancing the transmission capacity and upgrading the fiber optical lightpath [8]. Dispersion is pulse broadening in an optical fiber. Light propagates in an optical fiber, and the parameters of the fiber, such as core diameter, refractive index, laser line width, and numerical aperture, will cause pulse broadening [9]. This pulse broadening leads to impairments in Fiber Optic Communication. Dispersion can be operated with the standard optical fiber, which has zero dispersion with the operational bandwidth at 1310 nm, or a lightpath system design with 1550 nm operating bandwidth for Dispersion Compensation Fibers (DCF) [10]. These impairments are classified as linear impairments and nonlinear impairments. Chromatic and Polarization Mode Dispersion and timing offset are classified under linear impairments. Nonlinear impairments include Self-Phase (SPM) and Cross Phase Modulation (XPM), Four-wave mixing (FWM), laser phase noise, and nonlinear phase noise [11]. Variations in Linear and Nonlinear characteristics generally vary along with fiber length. Revolutionary and evolutionary developments in telecommunication led to the implementation of many methods for compensating dispersion in fiber optics. This Chromatic Dispersion limits data and bandwidth [12]. In real-world applications, the 1550 nm band involves higher applications and provides better operation for long-haul lightpath establishments. The practical implementation of fiber amplifiers and low attenuated fibers allows WDM technologies to be highly compact, have efficient design, and have economic benefits [13].

Dispersion compensation techniques have been researched extensively to tackle dispersion challenges in fiber optic communication systems. Recent studies by [14] and [15] have focused on innovative approaches to dispersion compensation, such as adaptive algorithms and advanced optical components. Dynamic dispersion compensation methods that use machine-learning techniques are discussed [16]. This approach has shown improved performance in real-time optical networks by adapting to changes in network conditions and optimizing dispersion compensation parameters. This results in better signal quality and transmission efficiency. Similarly, [17] explored the use of nonlinear optical elements for dispersion compensation. They demonstrated that specific optical components, such as nonlinear fibers or optical amplifiers, could be used to effectively counteract dispersion-induced signal distortion. This approach provides promising results regarding improved signal quality and transmission efficiency.

While these recent works offer valuable insights into dispersion compensation techniques, this paper comprehensively reviews and analyses passive and active dispersion compensation methods [18]. By synthesizing findings from previous studies and evaluating the effectiveness of various compensation techniques, this paper aims to provide a thorough understanding of dispersion management in fiber optic communication systems. In contrast to the most recent studies by [19] and [20], this paper aims to delve deeper into dispersion compensation techniques, encompassing a broader spectrum of passive and active approaches. While Smith et al. primarily focus on a particular aspect of dispersion compensation dynamic adaptation through machine learning algorithms [21]. This paper strives to thoroughly examine various compensation methods, including passive techniques like fiber Bragg gratings and dispersion-compensating fibers [22].

Similarly, with the utilization of nonlinear optical elements for dispersion compensation, this paper aims to evaluate a more comprehensive array of compensation techniques and their suitability across different optical network scenarios [23]. By conducting a comparative analysis of passive and active methods, [24] offers readers a unique understanding of the strengths and limitations of each approach. Ultimately, this facilitates more informed decision-making in optical system design and implementation [25]. However, recent studies have contributed valuable insights to the field of dispersion compensation, and this paper endeavors to build upon their work by offering a comprehensive review and analysis of dispersion compensation techniques [26]. Through this research approach, we aim to enrich the existing body of knowledge in the field, providing researchers and practitioners with a more nuanced understanding of dispersion management in fiber optic communication systems. The dispersion effects can be minimized using different fiber structures. However, fiber with different structures can cause other nonlinear effects, such as four-wave mixing (FWM), which degrades the data transmission efficiency in WDM systems [27]. This study delves into the different types of compensation and the various compensation techniques involved in the optical lightpath system design. The comparison of compensation techniques can clarify the performance of the WDM-based lightpath communication [28]. However, this review will help researchers understand the theoretical approaches, comparative advantages of the existing approaches, and difficulties with practical implementation. Over the years, dispersion compensation research has evolved, resulting in the development of various methods to address the challenges posed by dispersion. Optical communication networks rely on the transmission of light signals through long distances. However, as light travels through fiber-optic cables, it can experience dispersion, which causes the signal to spread out and become distorted [29]. Dispersion compensation techniques have been developed to mitigate these effects and maintain signal quality. Dispersion compensation techniques can be broken down into passive and active methods. Passive methods use dispersion-compensating fibers (DCFs) or fiber Bragg gratings (FBGs) to modify the signal's wavelength and counteract dispersion [30]. On the other hand, active methods use digital signal processing (DSP) techniques to manipulate the signal's phase or amplitude. Over time, research has improved in designing and optimizing dispersion compensation modules. Additionally, a better understanding and modeling of dispersion characteristics have allowed for more effective mitigation methods. As a result, many existing methods have been successfully applied in real-world optical communication networks. Passive methods, such as DCFs, offer cost-effective dispersion compensation solutions, making them an attractive option for network operators [31]. These methods have demonstrated practicality and effectiveness in mitigating dispersion effects, ensuring reliable signal transmission.

However, in optical communication systems, dispersion is a significant obstacle that impairs the signal quality during transmission. Dispersion compensation techniques are used to mitigate this effect and improve signal quality. Passive dispersion compensation methods, such as dispersion-compensating fibers and fiber Bragg gratings, are limited in adapting to changing network conditions [32]. These techniques may not work efficiently in a dynamic or heterogeneous network environment. Active methods, such as DSP-based dispersion compensation, require advanced hardware and software for real-time processing. These methods can be complex and expensive, particularly in large-scale networks. Integrating specific dispersion compensation techniques with existing optical network infrastructure can be challenging due to compatibility issues, especially with legacy systems [33]. Although current dispersion compensation techniques are effective, there is a requirement for improvement in achieving higher data rates and longer transmission distances with minimal signal distortion. Therefore, further research and development of dispersion compensation techniques are necessary to address the emerging requirements of modern optical communication systems.

This research investigates the problem of dispersion compensation in dynamic network environments. Dispersion is an unavoidable phenomenon that results in signal distortion and loss of information during transmission. To address this issue, we explore adaptive dispersion compensation methods and real-time monitoring techniques that dynamically adjust compensation parameters. Our work involves integrating advanced technologies such as nonlinear optics and signal processing techniques to improve the efficiency and effectiveness of dispersion compensation. Furthermore, it focuses on passive and active compensation techniques to optimize performance across various network scenarios and conditions, enabling us to provide seamless integration with existing optical infrastructure. This can be achieved through proposing novel strategies and methodologies for designing and implementing dispersion compensation systems. These approaches include innovative methods for compensating for chromatic, polarization mode, and modal dispersion. We can ensure that the network performs optimally in different conditions by improving signal quality and transmission efficiency. Our comprehensive approach involves extensive testing and validation of dispersion compensation methods to provide robust empirical evidence supporting our findings and conclusions. We build upon the strong foundation of prior research by addressing limitations and exploring new frontiers in optical communication. Our ultimate goal is to contribute to advancing the field and driving innovation in dispersion compensation techniques, ultimately improving the quality and reliability of optical communication.

This work presents a novel contribution to dispersion compensation techniques in fiber optic communication systems. Our research addresses a critical gap in the existing literature by thoroughly examining and analyzing passive and active dispersion compensation methods. The primary objective of this work is to investigate the evaluation methods, potential improvements, and implementation for enhancing the quality of data transmission in real-world lightpath establishments. By the findings of prior studies and assess the efficacy of various compensation techniques. As a result, we gained valuable insights into dispersion management strategies that ensure the uninterrupted delivery of broadband services in today's digital landscape. Our systematic approach has advanced the understanding of dispersion compensation techniques and provides the way for further research and development in this area. This work can potentially improve the performance and reliability of optical communication systems. Furthermore, it also contributes to the advancement of telecommunications technology in the post-COVID-19 era. Additionally, this review contributes to the current advancements in compensation techniques, enhancing the reliability, scalability, and performance of lightpath communication networks.

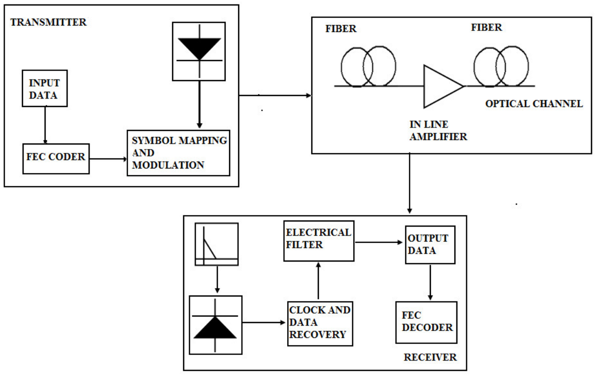

Figure 1. Optical Link Block diagram

The paper is organized into various sections: In Section 3, we discuss the various types of dispersion and their requirements for the compensation techniques. Section 4 briefly explains the different dispersion compensation techniques in fiber optical communication. Section 5 compares the various dispersion compensation techniques discussed in Section 4. However, Section 6 presents the performance metrics that determine the transmission quality. Finally, Section 7 discusses the conclusion and future scope of the research work.

## 2. METHODOLOGY

In this research, we conducted a thorough and systematic search of academic databases such as IEEE Xplore, PubMed, and ScienceDirect. This search aimed to find the latest research on dispersion compensation techniques for fiber optic communication systems. We focused on studies that addressed chromatic dispersion and polarization mode dispersion, two significant factors limiting the performance of fiber optic systems. We included studies that discussed passive and active dispersion compensation techniques to identify the most effective strategies for improving system performance. To ensure the highest quality of research, we selected studies based on their relevance to our research topic, publication date, and the quality of the work. We also excluded papers that did not directly address dispersion compensation in fiber optic systems or needed more data for analysis. We collected important information from each study, including dispersion compensation techniques, performance metrics such as bit error rate and signal-to-noise ratio, network scenarios, and any unique contributions of the work. After collecting this data, we categorized the selected studies into passive and active compensation methods and evaluated the performance of each approach under different network conditions. We evaluated the quality of each study by examining its methodology, data analysis, and the strength of its conclusions. Potential biases and limitations were taken into consideration during the evaluation process. In addition, we performed a comparative analysis of the different methods used across studies to identify trends, strengths, and weaknesses in dispersion compensation techniques.

This research is aimed to provide a detailed and comprehensive understanding of dispersion compensation research. Here, we have conducted a thorough systematic review of various studies, analyzing the performance of different methods. The results of our analysis have been presented in tables, offering a clear and concise overview of the key findings from each study. In addition to the tables, we have provided a narrative synthesis of the findings, highlighting patterns and trends that have emerged from the research. This includes a detailed discussion of each method's strengths and limitations, as well as the challenges that researchers face in this area. Through our analysis and synthesis of the research, we aim to provide a valuable resource for those interested in dispersion compensation. By presenting a comprehensive overview of the state of research, we aim to facilitate further advancements in this field and encourage the development of new and innovative methods for improving dispersion compensation.

## 3. TYPES OF DISPERSION

In fiber optics, dispersion refers to spreading the optical signal as it travels through the fiber. This can result in loss of signal quality and limitations on the distance over which the signal can be transmitted. There are two types of dispersion: intramodal and intermodal dispersion effects.

### A. Intermodal Dispersion

For short-distance communication, multimode fiber is developed to transmit the light, which utilizes multiple beams of light, propagates at different angles, and achieves effective transmission [34]. These fibers introduce phenomenal effects and cause pulse spreading, known as intermodal dispersion. In intermodal dispersion, the fundamental mode operates the light beam and travels along with the fiber, whereas, in critical mode, the light beam propagates and travels at the critical angle. These two modes will travel different distances at different time intervals and reach the destination, which causes the pulse-broadening effects and finally leads to intermodal dispersion [35]. This results from the modes, which travel at different speeds and exhibit time delay. This process introduces more distortion in the transmitted signal and accumulates pulse-broadening errors in the data transmission. It is necessary to understand that intermodal dispersion can extend more based on various other factors like the fiber's core diameter, numerical aperture, and refractive index of the fiber [36]. Through exploring the intermodal dispersion concepts and mechanisms, researchers can implement the lightpath system that reduces the effect and enhances the accuracy of the data transmission.

### B. Intramodal Dispersion

Intramodal dispersion arises because the different frequencies of the optical beam travel through the different fiber materials and the waveguide structure [37]. As the optical pulse transmits into the fiber, the higher wavelength can propagate faster than the lower wavelength. This introduces the pulse-broadening effect and deteriorates the quality of the signal. This phenomenon accumulates more noise and occurs in both single and multimode fiber. Intramodal dispersion can be classified into chromatic dispersion and modal dispersion. Chromatic dispersion occurs When different wavelengths of light travel through the fiber at different speeds. However, the modal dispersion arises due to the propagation of light waves into the various modes of the optical fiber [38]. This dispersion effect can elevate the pulse-broadening effects, disturb the quality of data transmission, and reduce the performance of the lightpath communication systems. In signal transmission, the presence of the finite spectral width causes Group velocity dispersion. This phenomenon carries the light information at different velocities depending on the wavelength of the signal [39].

Furthermore, gaining knowledge of different types of dispersion will help fiber optic engineers design and implement an effective lightpath model. This can help transmit the data in long-haul communication without compromising the signal quality. Chromatic dispersion also depends on the refractive index of the optical fiber. It is defined as the ratio of light traveling in an optical medium to that of a vacuum. The effective refractive index of the fiber is defined as 1.45 [40]. Optical amplifiers, DCF, and FBGs are utilized in a lightpath system design to overcome chromatic dispersion. This phenomenon arises due to the factors such as the longer distance of the fiber and shifting the operating wavelength. In signal regeneration, increasing the fiber length from 100 m to 100 km under the bandwidth 1.53 µm to 1.56 µm provides a higher chromatic dispersion [41]. For single-mode fiber, when the different frequency components of the light can travel at different speeds, it leads to chromatic dispersion. Lasers with minimal spectral widths optimized for an individual wavelength are widely used in lightpath transmission. However, these components cannot eliminate the chromatic dispersion effects. However, this can help reduce the effects of chromatic dispersion [42].

### 1) *Material Dispersion*

Material dispersion occurs due to the dependence of the refractive index of the optical fiber on the wavelength. This causes pulse-broadening effects since each wavelength component of an individual pulse travels at different velocities [43]. The group velocity of the fiber's mode always depends on the wavelength, which results in the pulse-broadening effects. This may occur even when the optical signal with different frequencies travels through the same light path. However, the impact of the material dispersion can be minimized by using a WDM transmitter with a narrow wavelength spectrum [44]. This enables the wavelength components that are present within the narrow band. Narrow spectral width lasers are widely used in a lightpath system design to overcome material dispersion effects. This dispersion depends on the refractive index of the core material. This effect is much smaller in multimode fiber than in single-mode fiber because of short-distance communication [45].

### 2) *Waveguide Dispersion*

When a light signal is transmitted into the optical fiber, which consists of the core and cladding region. The core region is the central part where most signals can propagate. However, a small portion of the signal can penetrate the optical fiber's cladding region, leading to a signal drop. [46]. The difference between the core and cladding region will define the refractive index profile of the optical fiber. This is a crucial factor that affects the quality of the signal transmission. The distance between the core and the cladding region influences the transmitted signal to travel at different velocities. The cladding region poses a lower refractive index than the core refractive index [35]. The signal that travels in the cladding region reaches faster to the end of the fiber than the signal that travels in the core region. This will introduce a higher difference in arrival time, which causes a dispersion effect known as waveguide dispersion. In this effect, the optical signal can be traveled through the core and cladding region of the optical fiber. This phenomenon can occur due to the fiber's core size variation, also known as the propagation mode constant [47]. As a result, waveguide dispersion has specific properties that are different from the material dispersion in multimode fibers. However, waveguide and material dispersions are highly correlated to the SMF, which has a minimal core diameter. In this fiber, variation in dispersion impairments is clearly based on the operating wavelength and through the silica material characteristics and waveguide properties. A deep knowledge of this phenomenon can enhance the design model and optimize the lightpath network for reliable and high-speed data transmission [48].

### 3) *Polarization Mode Dispersion*

A SMF carries two linear polarized waves that travel in two perpendicular planes. Each mode carries half of the total optical power. However, due to the asymmetry in the optical fiber during the cabling and splicing process, the refractive index of these planes is different. This difference leads to polarization dispersion, which is a complex dispersion [49]. Polarization impairments are significant issues in increasing the data transmission rate in WDM systems. Optical fibers can experience impairments, affecting their performance in lightpath connections. Polarization mode dispersion (PMD) and Polarization Dependent Loss (PDL) are the two types of impairments that generally occur in passive optical components [50]. These impairments can also cause polarization-dependent modulation (PDM) in electro-optical modulators and polarization-dependent gain in fiber optic amplifiers. Materials like fiber have different refractive indices for each device in the light wave, known as birefringence [51]. The magnitude of PMD in fiber is expressed as the difference between the refractive indexes of the two planes and is indicated as $\Delta\tau$, known as the Differential Group Delay (DGD).

### 4) *Reason for Dispersion Compensation*

Fig. 2 shows the representation of a DWDM system with its nonlinear impairments. In fiber optic communication, data signals with different wavelengths will experience different delays due to their dependence on the refractive index. This causes the signals to spread and overlap, resulting in Inter-Symbol Interference (ISI) when the data rate increases. As a result, the data rate cannot be increased beyond a specific limit without dispersion compensation [52]. Dispersion Compensation is essential for achieving high data rates in fiber optic communication links [53]. As the data rate of a single channel approaches 1TB/s, it becomes necessary to consider compensating for the wavelength dependence of chromatic dispersion.

In lightpath connections, chromatic dispersion can be reduced in many ways. Components such as FBGs, optical amplifiers, electronic dispersion compensation, modulation formats, and DCFs can overcome chromatic dispersion's effects [54]. However, DCF is frequently used for this compensation because of its stability, wider bandwidth, and resistance to adverse temperature deviations. DCF has insertion loss limitations also. The core region of this compensating fiber is highly doped, which results in negative

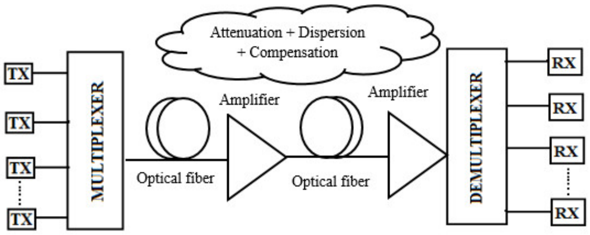

Figure 2. WDM system design with impairments

dispersion effects. The negative dispersion range of this fiber is defined as-70 to-90 ps/nm [1]. The performance of the optical WDM system design can degrade due to the accumulation of ASE noise caused by periodic amplification, Kerr nonlinearity, and group velocity dispersion [55]. Therefore, it is essential to ensure that DCF has low insertion loss, low Polarization mode dispersion, low nonlinearity, and a small size to guarantee a significant chromatic dispersion coefficient.

The direct modulation technique, NRZ on-off, is often used with an extensive frequency modulation on chirp that increases with the bit rate [56]. Circuits designed at the receiver end incorporate APD, gain clock recovery, and a decision circuit. Regeneration can limit optical noise, linear distortion, and nonlinearity to ensure a clear signal.

## 4. DISPERSION COMPENSATION TECHNIQUES

In lightpath communication, the data transmission is performed at the speed of light, travels long-haul distances, and is highly appreciable for reliability. The optical signal carries multimedia, and other data information will be challenged due to the dispersion effects. This arises mainly due to different wavelengths of light traveling at different velocities through the optical fiber. This dispersion can broaden the signal and spread over the distance, which results in signal degradation and limits the capacity of the lightpath network communication. Several dispersion compensation techniques and methodologies are devised to counteract the effects of the dispersion phenomenon. This section explores the various dispersion compensation techniques that have been employed to mitigate the dispersion and nonlinear-related issues in lightpath communication. The dispersion compensation techniques discussed here are Electronic Dispersion Compensation, Dispersion Compensation Fiber, Optical Phase Conjugation, Fiber Bragg grating, and Digital Filter technique

### A. Transmitter Spectral Shaping

Transmitter Spectral Shaping is a simple technique to generate a bit stream chirp by adding a modulated phase signal with a balanced MacZehnder amplitude modulator [57]. A frequency-modulated laser in a fiber optic signal enters an external modulator and achieves chirp. Simple laser-derived signals are proper frequency sinusoidal phases with the same bit rate [58]. In dispersion-supported transmission modulation, the transmitter generates a failed FM signal to the length of the span. Span with dispersion changes the transmitted FM signal into AM at the receiver. In direct detection, this leads to a phase-dispersion signal when the optical signal is combined with the photodiode [59]. When the dispersed signal can't compensate for a large dispersion, linear equalization is used. The main problem of dispersion-supported transmission is obtaining a good broadband FM response, which must decode a three-level optical signal at the receiver end [60].

### B. Data Recovery at the Receiver

In order to compensate for the receiver, a coherent or direct detection method can be used. A coherent receiver that combines input Signals with a local oscillator will introduce phase and amplitude variations to the optical carrier signal. However, electronic carrier signals can be compensated for linear dispersion [61]. Chromatic dispersion can result in signal distortions, but they are constant and predictable. Coherent detection is beneficial in long-haul WDM systems because it can directly compensate for detection errors. The logical complexity of this method increases exponentially with the number of pulse-broadening bits represented by 2n.

### C. The Optical Regime

Different categorized optical regime techniques for dispersion compensation are listed below.

#### 1) Interferometer

In an interferometer, signals of different spectral components travel along paths of varying lengths to compensate for dispersion. The Mach Zehnder Interferometer splits lights into two unequal lengths and recombines them using a $2 \times 2$ optical combiner [62]. The phase with delay plays a critical role in distributing light between the two output ports. A cascade interferometer with adjustable path length directs blue and red light through long and short arms. The interferometer has limited capacity for compensation due to its narrow bandwidth and polarization-dependent operation. However, the cascaded Mach–Zender's periodicity may enable simultaneous compensation for all channels in WDM systems [52].

#### 2) Fiber Bragg Grating (FBG)

Fig. 3 represents the DWDM system design using FBG. Optical FBG is vital in analytical applications of dispersion compensating in long-haul WDM systems [63]. Chirped fiber gratings are passive devices with low insertion loss used in long-haul communication. Fiber gratings are located as a line system to obtain optimum results since they have various advantages, such as less area, dispersion slope compensation, low insertion loss, and negligible nonlinear effects [64]. Optical system design using FBG is complex. FBGs that recompensate the dispersed optical signal are mainly used as compensation for chromatic dispersion. Due to the high interaction of Self Phase Modulation in FBG, it can extend the transmission distance in a point-to-point system [65]. GVDs are compensated significant improvement to BER performance is possible, depending on the fiber length and the chip rate. Chirped FBG prefers DCF due to its advantages [66].

FBGs allow light to resonate within a grating structure by satisfying the Bragg condition. Only a small portion of the signal is obtained through this reflection, while the remaining amount exits in the fiber. [66]. FBG reflects various frequencies at different wavelengths and has different signal frequency components with varying phase delays. These FBGs have a smaller length, approximately 10 to 15 cm, and are not suitable for WDM applications due to their narrow bandwidth of 0.12-5 nm [67]. Despite this drawback, FBGs have very low loss, around 1dB in 80km, and the shorter wavelength provides fewer nonlinear operations.

FBG, as a refractive device with reflected wavelength $\lambda_B = 2n\Lambda$, is called Bragg wavelength. These passive optical fiber devices are compatible, with very low cost and insertion loss. FBGs are used as sensors, frequency stabilizers for pump lasers, add-drop filters in narrowband WDM, and filters to compensate for dispersion [68]. The working principle of FBGs depends on the reflection of light from grating fringes and the coupling of the modes [69]. Coupling effects are created when forward and backward propagation fields interact in the same mode.

*a) Bragg constraints:-*

$\beta_1 - \beta_2 = \frac{2m\pi}{\Lambda}$, where $\beta_1$ and $\beta_2$ phase constant of two modes, $\wedge$ period of the variations in the refractive index, $m$ is the order of diffraction and it is 1 for $1^{st}$ order, and 2 with identical counter propagation modes $\beta_2 = -\beta_1$ and the Bragg condition becomes $2\beta = \frac{2m\pi}{\Lambda}$ now. Effective modal index is $\eta_{\text{eff}}$ then $\beta_1 = 2\pi\eta_{\text{eff}}/\lambda$ the Bragg conditions then gives the wavelength called $\lambda_B$ and $\lambda_B$ is represented as $2\eta_{\text{eff}}\Lambda$ [70].

*b) For Uniform Bragg grating:-*

Bragg grating with Forward and Backward amplitudes are given as $\frac{dR}{dZ} + j\sigma R = -jKS$ and $\frac{dS}{dZ} - j\sigma S = -jKR$ where $\sigma$ = DC coupling coefficient which is equal to $2\pi\delta_n/\lambda_B + \delta$, where $K$ = AC coupling coefficient = $\pi\delta_n/\lambda$ where $\delta$ detuning parameter [68].

*c) For Non-uniform FBG:-*

$n(z) = \delta n(z)\{1 + \nu\cos(2\pi z/\Lambda + \phi(z)\}\nu$ : FBG visibility lies on 0 and 1 $\phi(z)$: FBG with the spatial chirp of, $\delta n(z)$ the function of slow variable $z\sigma : 2\pi\delta n/\lambda_B + \delta - 0.5d\phi/dz$ and $k = \pi\delta n(z)/\lambda$. Gratings are placed with ordered intervals in uniform grating. Grating with a non-uniform structure is present in Chirped grating, whereas gratings with ordered arrangements are used to design Tilted grating; ordered group gratings are the concepts of Superstructure gratings [51].

### *3) Negative Dispersion Fiber*

SMF with negative dispersion is considered as a Negative DCF. This effect is achieved through a weakly guided mode, in which even a slight variation in the wavelength can cause significant changes in mode size [1]. The difference in the guided mode leads to increased attenuation and bending loss, which can be used to compensate for positive dispersion in optical fibers. In dispersion compensation techniques, LP11 mode fiber is used over LP01 mode fiber as it provides more negative dispersion [29]. However, mode conversion is required between the fundamental LP01 (lower order) and LP 11 higher order modes to achieve this negative dispersion. LP11 mode fiber is used because it has a larger mode area, which results in a higher overlap with the core of the optical fiber, thereby enabling a more significant negative dispersion value [45]. However, using SMF with negative dispersion can be highly beneficial in optical fiber communication systems as it helps compensate for the positive dispersion present in optical fibers. LP11 mode fiber can provide even more negative dispersion but requires a mode conversion between LP01 and LP11 modes.

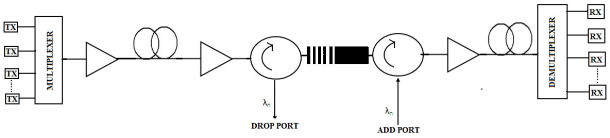

Figure 3. WDM system design with FBG

### *4) Electronic Dispersion Compensation*

Electronic equalization approaches are essential for mitigating the effects of dispersion in optical communication systems. When linear distortion occurs in the optical domain, such as chromatic dispersion after optical-to-electrical conversion, it is detected directly at the receiver [71]. Unfortunately, this linear distortion can lead to nonlinear distortion, a significant problem in electronics equalization techniques due to the implementation of nonlinear channel modeling and cancellation. To address this issue, various structures like Feedforward equalizers FFE, decision feedback equalizers (DFE), and maximum-likely hood sequence equalizers (MLSE) are employed in the electronic equalization technique [72]. Figs. 3 and 4 show the electronics dispersion compensation methods, such as DFE and FFE, that were discussed for better data transmission.

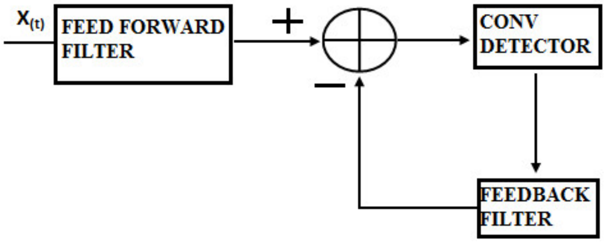

Figure 4. Single stage Decision feedback Structure

In fiber optic communication systems, the first-order polarization mode dispersion of the signal can be compensated for the complementary polarization mode dispersion at the receiver. The dispersion, which causes ISI, is mitigated by using a delay line with a gain stage-based integrated and distributed transversal equalizer [73]. Additionally, adaptive equalization is used to eliminate dispersion in ultra-high speed coherent fiber optic systems, allowing for compensation of device dispersion up to 1000 km of standard SMF [74].

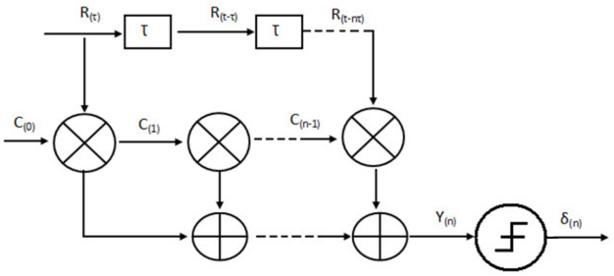

Figure 5. Feed Forward Equalizer

The Asymmetric Mach Zehnder interferometer's maximum order derivative time delay can significantly reduce thermal noise and nonlinearity in optical fiber. A slope dispersion equalizer is utilized in spectral amplitude coding optical CDMA systems with array-guided wave grating [75]. Good MZM and EDF amplifier SNR are crucial for optimizing the performance of ROF devices. CD and PMD are compensated for using an LMS adaptive equalizer. A nonlinear equalizer lie MLSE is employed to compensate for the ISI caused by this equalizer [76]. An adaptive algorithm-based filter design compensates for the dispersion in multimode fibers [76]. Adaptive compensation for chromatic dispersion in ultra-long haul WDM links is achieved using OFDM and OSSBCM (optical single sideband modulation). OFDM has the advantage of replacing DCF with EDFA, but an optical amplifier is required [77]. Fig. 6 shows the implementation of the DWDM system using the optical phase conjugation (OPC) block.

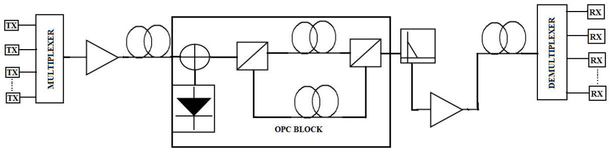

Figure 6. WDM system design with OPC Block

### 5) Digital Filter

Digital filters with DSP algorithms are mainly designed to compensate for chromatic dispersion. It provides a static and tunable compensating method for the WDM system. A lossless all-pass optical filter is used to compensate for dispersion using digital communication filters [77]. Other filters such as DPF, Gaussian, super-Gaussian, Butterworth, and microwave photonic filters are used [78]. Super-Gaussian filter, which can be an entirely suppressed phase jitter with control over self-frequency shift in ultra-optical pulse Butterworth filter, is also used to suppress phase jitter with better control than the conventional Gaussian filter. Super-Gaussian and Fabry Perot filters can overcome the noise effects in Semiconductor Optical Amplifiers, EDF Amplifiers, and Raman amplifiers. [79]. Further, it will reduce dispersion and attenuation effects. This will lead to improved long-haul WDM system performance. FIR filters are used to compensate for the polarization mode and chromatic dispersion. LMS algorithm-oriented system designs are more tolerant to chromatic dispersion and carrier phase noise than existing filters [52]. Since EDFA provides significant gain, regenerators are not used.

### 6) Dispersion Compensation Fiber

Chromatic Dispersion is dependent on the refractive index of the wavelength, causing temporal broadening of the pulse. Different frequency components of the light wave express different phase delays due to changes in refractive index. This phase difference distorts the signal characteristics. DCF is a widely used technique that compensates for dispersion at 1330 nm and 1550 nm. It has three schemes with NRZ link through FBG compensator to achieve a high data rate in optical transmission [80]. Different modulation techniques are used to increase the $Q$ factor and improve eye-opening. Optical fiber is advisable for achieving massive bandwidth and excellent transmission performance. It plays an essential role in data transmission and information communication. Dispersion Compensation Fiber is widely deployed to upgrade the implemented 1310 nm optimized fiber link for 1550 nm. A component fiber with a small length is used to achieve a high dispersion coefficient. Spans made of SMF and DCF are good options as their higher local dispersion has been proven to reduce phase matching, which leads to Four-Wave Mixing in WDM [81].

#### a) Pre Dispersion Compensation Fiber Technique:-

Pre-dispersion compensation techniques involve placing the DCF adjacent to the optical transmitter or before SMF for positive dispersion Compensation. In addition to dispersion, other losses are present in the transmitter signal [82]. Fig. 7 shows the pre-dispersion compensation design using a DWDM system. An EDFA is used at the optical end, and an LPBF is used at the electrical end to minimize these losses. The EDFA setup starts with the co-propagating pump scheme input signal, operated in the C-band wavelength range.

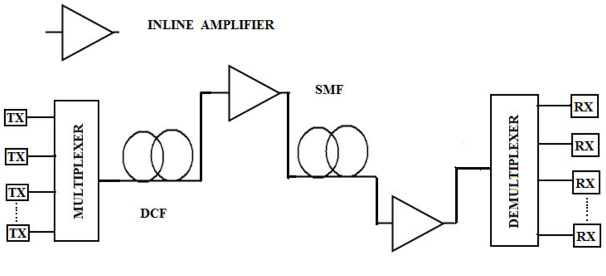

Figure 7. Pre-dispersion Compensation system design

#### b) Post Dispersion Compensation Fiber Technique:-

Post-dispersion compensation involves placing DCF after an SMF or before an optical transmitter to achieve positive dispersion compensation. An EDFA is used at the optical end, and an LPBF is used at the electrical end to eliminate different losses from span and DCF [83]. This setup is also implemented using EDFA co-propagating pump schemes, where an input signal is operated at the C-band wavelength. Fig. 8 shows the post-dispersion implementation in a DWDM system.

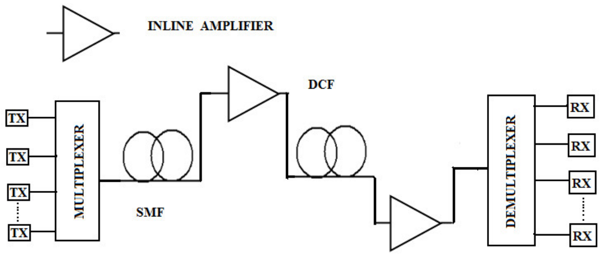

Figure 8. Post-dispersion compensation system Design

*c) Combined DCF Technique:-*

Fig. 9 shows the symmetric or combined compensation design for the DWDM system. The dispersion compensation for the nonlinear problems is challenging in lightpath communication systems. The symmetrical compensation technique is a practical approach that reduces the bit error rate and enhances the performance of the proposed system [83]. However, an increase in fiber length introduces higher BER, reducing performance. In order to combat this, an EDFA can be connected before and after the dispersion compensation fiber, which avoids signal loss and distortions. This kind of effective implementation results in wider bandwidth operations and effective spectral characteristics and enables smooth dispersion compensation.

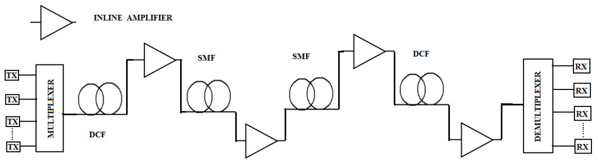

Figure 9. Combined compensation system design

## 5. COMPARISON SUMMARY

The systematic review of dispersion compensation techniques in fiber optic communication systems provides valuable insights into the field's current state and potential for future advancements. The findings have significant implications for designing and optimizing modern optical networks, offering guidance for researchers, engineers, and network operators. The review also highlights the importance of dispersion compensation techniques in optical networks. These techniques can significantly improve network reliability and performance by reducing signal distortion caused by dispersion. Enhancing data transmission quality can improve overall network efficiency. The review emphasizes the potential of adaptive compensation methods, such as machine learning-based techniques, to adjust dispersion compensation dynamically in real-time. This adaptability is essential for managing changing network conditions and optimizing performance. Moreover, the review identifies promising approaches for developing optical communication technologies, such as nonlinear optics and advanced signal processing methods. This research could revolutionize network infrastructure and drive progress in the field. However, some methods, such as active techniques, may pose scalability challenges, while others offer cost-effective solutions for dispersion compensation. The review highlights the importance of balancing cost-effectiveness with scalability when selecting solutions for practical deployment.

The review focused only on literature, which could limit the scope of the findings. Earlier work may need to be fully represented, affecting previous approaches. The quality and methodology of the studies reviewed varied, which could introduce some bias or inconsistency in the overall analysis. The review aimed to address this issue through critical appraisal, but it remains a limitation. Direct comparisons can be difficult since performance metrics and experimental setups differ across studies. The need for standardized metrics may also affect the generalizability of the findings. Research on adaptive and nonlinear methods for dispersion compensation shows potential for dynamic network management and optimization. Integrating dispersion compensation with emerging technologies such as quantum communication and 5G/6G networks could lead to transformative advances in optical communication. Investigating these methods' long-term performance and reliability in real-world networks is essential. Interdisciplinary collaborations can drive innovative solutions across various disciplines. Developing standardized metrics and benchmarks for assessing dispersion compensation methods would facilitate direct comparisons and the identification of best practices.

For years, various research methodologies have been proposed for dispersion compensation techniques. Table I shows a comparison summary of the researcher's contribution in this area. Each approach has its merits and demerits. The proposed lightpath design clearly has specific requirements based on user requirements. Generally, the compensation technique that uses DCF is preferred due to its simple system design and ability to handle wider bandwidth demands.

## 6. PERFORMANCE METRICS

In lightpath communication, several methods are used to monitor the performance metrics that estimate the quality of data transmission. These include:

### A. Spectral Eye Characteristics

Eye characteristics are mainly used to predict signal quality by monitoring the amplitude over the frequency and phase characteristics over a certain time [83]. A proper eye-opening defines the signal free from distortion. However, the distorted spectral characteristics indicate the signal with higher dispersion. The BER measurements are challenging to identify the jitter and noise characteristics

TABLE I. Comparison summary of dispersion compensation techniques

| Compensation Technique | Merits | Demerits |
|---|---|---|
| Dispersion management [41] | Inhibit FWM, average dispersion reaches to zero | Availability of Limited wavelength ranges, complex cable management |
| Un-equal channel spacing [84] | Low FWM crosstalk directly for a few channel systems | Wider bandwidth, rigorous requirements on optical frequency Stability |
| Optical compensator [85] (e.g.: Optical phase conjugation) | Actualize in-line compensation directly | Physical size, nonlinearity, Huge-cost, excessive loss, and adaptation delay |
| Non-Zero Dispersion Supported Fiber [80] | Applicable for future WDM system design. | The problem with fiber installation |
| Pre-compensation [86] | Reduced chromatic dispersion High-quality signal transmission Cost-effective Need of optical Solutions | Limited Range of Dispersion Compensation Less effective compared to other modes Need a feedback system for transmission characteristics analysis |
| Post-compensation [82] | Need of optical solutions, flexible, no Feedback. Wider bandwidth Compensation Adaptable for various configurations Simple maintenance and deployment | Number of detectors, Computation power. Residual dispersion The problem for ultra-long-distance transmission. |
| DCF in single channel system [9] | Minimal insertion loss High signal quality Efficient data transmission Less design complexity | An increase in length leads to high cost Highly influenced by nonlinearities signal distortion and lowers the system performance |
| CFBG in single-channel systems [9] | Accurate and adaptive compensation method Effective integration for lightpath devices Highly precise. | High Insertion Loss complex for manufacturing not advisable for large amounts of dispersion |
| DCF in Multichannel systems [53] | Provides broadband dispersion compensation simultaneously dispersion compensation | Limited bandwidth and data rate for transmission. |
| CFBG in Multichannel systems [87] | Enable precise compensation Highly accurate and Adaptive compensation for specific bandwidth | Less effective for multiple channels Increasing channels leads to an increase in FBG length |
| Hybrid Module [82] | Comprehensive solution<br>Increased Accuracy<br>User-based customization. | Complex structure Difficult to maintain |
| Symmetrical compensation mode [83] | Improved Signal Quality<br>handle a wider range of application<br>Most efficient compensation mode | Design and Implementation difficulties |

that degrade the lightpath performance. Spectral eye characteristics provide higher insights into both degradation characteristics and calculate the extinction ratio [88]. For error-less transmission, the spectral eye's height is higher than the dispersion effects that lower the eye height.

### B. Minimal BER

BER is defined as the presence of error in a lightpath network system. Minimal BER shows the signal characteristics with few errors and achieves high signal quality. Optical transmission refers to the required minimal BER for an effective data communication range of $10^{-9}$ to $10^{-15}$ [89]. The operating conditions and requirements of the system determine the lower BER requirements for an efficient optical link. In general, spectral eye characteristics with minimal BER are defined as the better quality for data transmission. It is also necessary to understand that various factors, such as fiber quality, receiver sensitivity, link power, and optical sources, can affect the quality of BER, which results from the estimation of lightpath quality transmission. [90].

### C. Q-factor

In general, the Q-factor denotes the performance of the lightpath receiver and monitors the noise sensitivity and data reliability. This metric measures the quality of the signal. The Q-factor's lower range determines the level of the optical signal's dispersion effects [91]. A higher Q-factor shows lower dispersive effects. Achieving a high q-factor can help to detect the low-intensity signal, which results in higher SNR and minimal BER. However, the DWDM system with a complex modulation format and higher data rate may be required to achieve minimal BER [21]. Meanwhile, the Q-factor is also affected by the factors defined in the BER section. Increasing the distance for a long-haul optical system will lower the Q-factor and show performance degradation.

### *D. Optical Signal-to-Noise Ratio (OSNR)*

OSNR is the critical factor determining data transmission quality in lightpath communication. It is defined as the ratio of the output signal power to that of the total optical power [20]. The unit to represent the OSNR measurements is decibels (dB), which influence the performance of the BER and Q-factor. The high value of OSNR denotes that the output signal is much stronger and attains a low noise level. This results from the characteristics received that result in low BER and higher Q-factor. The minimal OSNR for better lightpath performance depends on the data rate and modulation format used to design the system [92]. For a single channel system with RZ modulation format, the required OSNR is 12–14 dB. Meanwhile, For NRZ format, the sufficient OSNR range is 10–14dB. For DWDM systems, the required OSNR always depends on channel spacing and the number of channels [93]. For an adequate dispersion compensation, higher OSNR is necessary, along with receiver sensitivity criteria.

## 7. Conclusion

In conclusion, this comparative study discusses the dispersion compensation techniques in an optical communication system. Dispersion can be a challenging factor in real-world scenarios, as it can negatively affect the quality of data transmission. This study aims to address these challenges and improve the performance and reliability of optical systems. Through a comprehensive review and analysis, the study highlights the significance of dispersion compensation techniques in maintaining the integrity of optical communication. Passive and active approaches, ranging from fiber Bragg gratings to digital signal processing methods, are discussed, and their effectiveness in mitigating dispersion effects is evaluated. The findings underscore the importance of a systematic approach to dispersion management, considering factors such as dispersion type, network dynamics, and compatibility with existing infrastructure. This research aims to inform more informed decision-making in optical system design and implementation by providing insights into the strengths and limitations of different compensation techniques. Real-world studies on dispersion compensation techniques in optical networks are valuable for validating their efficacy. This study provides insights into crucial dispersion management strategies for seamless broadband service delivery in digital landscapes. Additionally, this research is a foundational resource for engineers, practitioners, and researchers in optical communications. The future scope of this review involves implementing adaptive dispersion compensation techniques and machine learning-based approaches to improve optical system performance in real-time by adjusting to changing networking conditions. Further research is needed to explore advanced dispersion compensation strategies that utilize emerging technologies such as machine learning and nonlinear optics.

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**Sudha Sakthivel** received a Master of Engineering with a specialization in Computer Science and Engineering in 2006. She is currently pursuing a Ph.D. degree in information technology at Universiti Kuala Lumpur with focus on Fiber Optic Lightpath Networks. She has several years of teaching experience in national and international universities. She has presented, served as the session chair at conferences and seminars internationally. Her research interests include in the fields of wireless sensor networks, Internet of Things, Compiler Design, Fiber Optic Networks, and Artificial Intelligence.

**Muhammad Mansoor Alam** is a Professor of Computer Science. He is recently associated with Riphah International University, Islamabad. He has also worked as an Associate Dean in CCSIS and HoD Mathematics, Statistics and Computer Science Departments of IoBM, Pakistan. Dr. Alam is enjoying 20 years of research and teaching experience in Canada, England, France, Malaysia, Saudi Arabia and Bahrain and authored 150+ research articles which are published in well reputed journals of high impact factor, Springer Link book chapters, Scopus indexed journals and IEEE conferences. He has honor to work as an online laureate (facilitator) for MSIS program run by Colorado State University, USA and Saudi Electronic University, KSA. Dr. Muhammad has also established research collaboration with Universiti Kuala Lumpur (UniKL) and Universiti Malaysia Pahang (UMP). Currently, Dr. Alam is also working as an adjunct professor in UniKL and supervising 12 PhD students.Dr. Alam has done PostDoc from Malaysia in "Machine Learning Approaches for Efficient Prediction and Decision Making". He has done PhD in Computer Engineering, PhD in Electrical and Electronics Engineering, MS in System Engineering and M.Sc. Computer Science from France, United Kingdom and Malaysia. Universite de LaRochelle awarded him Très Honorable (with distinction) PhD due to his research impact during his PhD.

**Aznida Abu Bakar Sajak** graduated from the University of Liverpool in 2005 with Master of Science (Engineering) in Telecommunications and Microelectronics Systems. Loves Liverpool so much that she decided to pursue her PhD in Electrical Engineering & Electronics at the same university sponsored by the Islamic Development Bank, Saudi Arabia. Was in Digi Telecommunications, a mobile service provider in Malaysia owned by Telenor ASA of Norway, for almost six years before joining UniKL in late 2011.

**Mazliham Mohd Suúd** received a master's degree in electrical and electronics engineering from the University of Montpellier, in 1993, and a Ph.D. degree in computer engineering from the Université de La Rochelle, in 2007. From 2013 to 2020, he worked as the President/CEO of Universiti Kuala Lumpur, Malaysia. Since 2020, he has been working as the President/CEO of Multimedia University, Malaysia. He has vast experience in publishing in high-quality international scientific journals and conference proceedings. He has numerous years of experience in the industrial and academic fields.

**Mohammad Riyaz Belgaum** received his master's degree with a specialization in computer applications in 2001 and a Master of Engineering with a specialization in Computer Science and Engineering in 2006. He completed PhD degree in information technology from Universiti Kuala Lumpur, Malaysia, in 2022. He is an Oracle Database 11g Administrator Certified Professional and an Oracle Database 11g Program with PL/SQL Certified Associate. Currently, he is working as an associate professor in the department of computer science and engineering at G. Pullaiah College of Engineering and Technology, Kurnool. He is also a post-doctoral researcher at Multimedia University, Malaysia, doing research on the application of blockchain for secure communication in WSN. His areas of interest include cloud computing, software defined networking, mobile ad hoc networking, wireless sensor networks, the Internet of Things, and bytecode analysis. He has authored more than 40 research articles published in journals and peer-reviewed conferences. He has vast teaching experience across various countries, with much focus on research.