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Review of Compensation and Dispersion Techniques for Fiber Optic Lightpath Networks

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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 that introduces more signal distortion and lowers the quality of data transmission. This research provides a detailed analysis of dispersion compensation techniques and their necessity for maintaining the integrity of optical communication. 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. 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. 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 and enhances the performance and reliability of the optical system design.

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

1. INTRODUCTION

After COVID-19, the exponential evolution of the multimedia industry requires massive broadband services. This leads to understanding the various optical lightpath and their working principles to meet the requirement of huge bandwidth applications. Wavelength division multiplexed lightpath connection enables faster communication 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 lightpath 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 for modulating 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].

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Penalties can be accumulating over the entire system length. Distributed feedback 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, eventually resulting in many errors [7].

Dispersion and nonlinear issues are the major 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 1550nm 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 the fiber amplifiers and low attenuated fibers allows WDM technologies for highly compact, efficient design and economic benefits [13].

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. 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. However, this review will help researchers understand the theoretical approaches, comparative advantages of the existing approaches, and practical implementation difficulties. The primary objective of this work is to explore the evaluation methods, further refinements, and implementation for improving the quality of data transmission in real-world lightpath establishments. Furthermore, this review also contributes to the current advancements of the various compensation techniques, which will enhance the reliability, scalability, and performance of the lightpath communication networks.

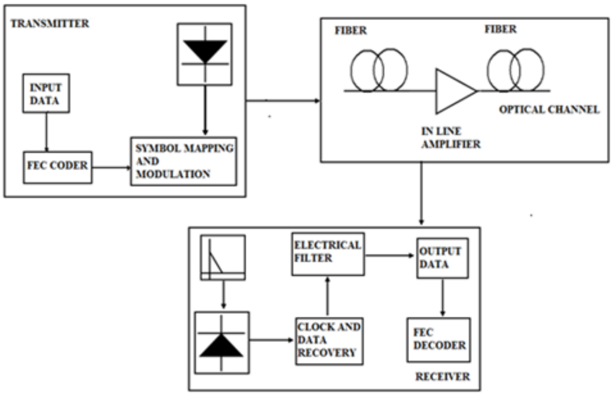

Fig 1. Optical Link Block diagram

The paper is organized into various sections as follows: In Section 2, we discuss the various types of dispersion and its requirements for the compensation techniques. Section 3 provides brief ideas about the different types of dispersion compensation techniques in fiber optical communication. Section 4 introduces the comparison of the various dispersion compensation techniques, which we discussed in Section 3. However, section 5 presents the performance metrics that determine the transmission quality. Finally, section 6 discusses the conclusion and future scope of the research work.

2. TYPES OF DISPERSION

In fiber optics, dispersion refers to the spreading of 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 [14]. These fibers introduce phenomenal effects and cause pulse spreading, which is 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 [15]. This results from the modes, which travels at different speed and exhibits 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 core diameter of the fiber, numerical aperture, and refractive index of the fiber [16]. 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 due to the fact that the different frequency of the optical beam travels through the different fiber materials and the waveguide structure [17]. 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 [18]. 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 [19].

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 [20]. Optical amplifiers, DCF, and FBGs are utilized in a lightpath system design to overcome the 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 100m to 100km under the bandwidth 1.53um to 1.56um provides a higher chromatic dispersion [21]. For single-mode fiber, when the different frequency components of the light can travel at different speeds, it leads to chromatic dispersion. In a lightpath transmission, lasers with minimal spectral widths optimized for an individual wavelength are widely used. However, these components cannot eliminate the chromatic dispersion effects. However, this can help to reduce the effects of the chromatic dispersion [22].

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 [23]. 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 lightpath. However, the impact of the material dispersion can be minimized by using a WDM transmitter with a narrow wavelength spectrum [24]. 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 the multi-mode fiber than in single-mode fiber because of short-distance communication [25].

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 of the signal can propagate. However, a small portion of the signal can penetrate the cladding region of the optical fiber, which leads to a signal drop [26]. The difference between the core and cladding region will define the refractive index profile of the optical fiber. This could be considered 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 [15]. 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 variation in the fiber's core size, also known as the propagation mode constant [27].As a result, waveguide dispersion has specific properties that are different from the material dispersion in multi-mode 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 [28].

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 present 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 [29]. Polarization impairments are significant issues in increasing the data transmission rate in WDM systems. Optical fibers can experience impairments, which can affect their performance in lightpath connections. Polarization mode dispersion (PMD) and Polarization Dependent Loss (PDL) are the two types of impairments that generally occurs in passive optical components [30]. These impairments can also cause to 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 [31]. The magnitude of PMD in fiber is expressed as the difference between the refractive indexes of the two planes and is indicated as $\Delta\tau$, which is known as the Differential Group Delay (DGD).

4) *Reason For Dispersion Compensation*

Fig.2 shows the representation of a DWDM system with their 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 out and overlap, resulting in Inter-Symbol Interference (ISI) when the data rate is increased. As a result, the data rate cannot be increased beyond a certain limit without dispersion compensation [32]. Dispersion Compensation is essential for achieving high data rates in fiber optic communication links [33]. As the data rate of a single channel approaches 1TB/s, it becomes necessary to consider compensating for the wavelength dependence of chromatic dispersion.

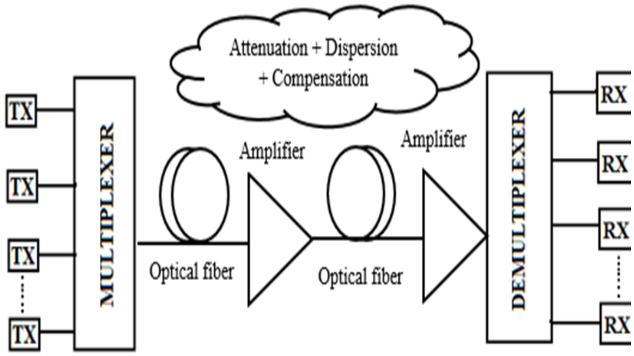

Fig 2. WDM system design with impairments

In lightpath connections, the presence of 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 [34]. 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 and results in negative dispersion effects. The negative dispersion range of this fiber is defined as -70 to -90ps/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 [35]. 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 in conjunction with an extensive frequency modulation on chirp that increases with the bit rate [36]. 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.

3. DISPERSION COMPENSION 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 dispersion phenomenon's effects. 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 [37]. Frequency-modulated laser in fiber optic signal, which enters an external modulator, achieves chirp. Simple laser-derived signals are proper frequency sinusoidal phases with the same bit rate [38]. 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 [39]. When the dispersed signal can't compensate for a large dispersion, linear equalization is used. The main problem of dispersion-supported transmission is to obtain a good broadband FM response, which is a must to decode a three-level optical signal at the receiver end [40].

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 [41]. Chromatic dispersion can result in signal distortions, but they are constant and predictable. Coherent detection is particularly useful in long0haul 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, which is 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 X 2 optical combiner [42]. 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 [32].

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 [43]. 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 it has various advantages such as less area, Dispersion slope compensation, Low insertion loss, and Negligible non-linear effects [44]. Optical system design using FBG is complex. FBGs that recompensate the dispersed optical signal is mainly used as compensation for chromatic dispersion. Due to the high interaction of Self Phase Modulation in FBG, it can be used to extend the transmission distance in a point-to-point system [45]. 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 [44].

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 [46]. 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 -5nm [47]. 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 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 [48]. The working principle of FBGs depends on the reflection of light from grating fringes and the coupling of the modes [49]. When forward and backward propagation fields with the same mode interact, it creates coupling effects.

Bragg constrains:

$\beta_1 - \beta_2 = \frac{2m\pi}{\Lambda}$ Where β 1& β 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 1st order, and 2 with identical counter propagation modes and the Bragg condition becomes $2\beta = \frac{2m\pi}{\Lambda}$ now. Effective modal index is ηeff then $\beta_1 = 2\pi\eta_{eff}/\lambda$ the Bragg conditions then gives the wavelength called λB and λB is represented as $2\eta_{eff}\Lambda$ [50].

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 = DC coupling coefficient which is equal to $2\pi\delta_n / \lambda_B + \delta$ Where K=AC coupling coefficient = πδn/λ where δ detuning parameter [48].

For non- uniform FBG:

$n(z) = \delta n(z)\{1 + \nu\cos(2\pi z/\Lambda + \varphi(z)\}$ ν **:** FBG visibility lies on 0 &1

$\varphi(z)$: FBG with spatial chirp of, $\delta n(z)$ function of slow variable z $\sigma : 2\pi\delta n/\lambda_B + \delta - 0.5 d\varphi/dz$ and $k = \pi\delta n(z)/\lambda$.

Gratings are placed with ordered interval in uniform grating. Grating with non-uniform structure is presents in Chirped grating whereas gratings with ordered arrangements are used to design Tilted grating, ordered group gratings are the concepts of Superstructure gratings [31].

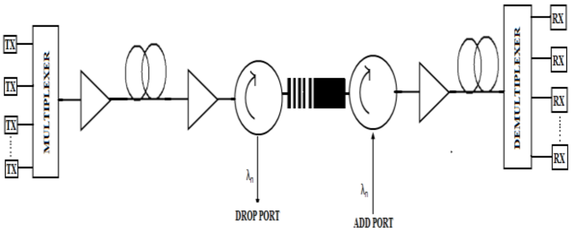

Fig 3. WDM system design with FBG

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 causes 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 [14]. However, mode conversion is required between the fundamental LP01 (lower order) and LP 11 higher order modes in order 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 larger negative dispersion value [25]. 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.

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 in the case of chromatic dispersion after optical-to-electrical conversion, it is detected directly at the receiver [51]. Unfortunately, this linear distortion can lead t nonlinear distortion, which is 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 [52]. Fig 3 and 4 shows the electronics dispersion compensation methods such as DFE and FFE discussed for better data transmission.

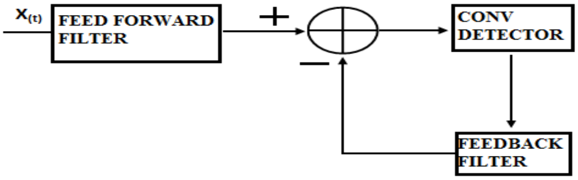

Fig 4. Single stage Decision Feedback Structure

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 [53]. Additionally, adaptive equalization is used to eliminate dispersion in ultra-high speed coherent fiber optic systems, allowing for compensation of device dispersion up to 1000km of standard SMF [54].

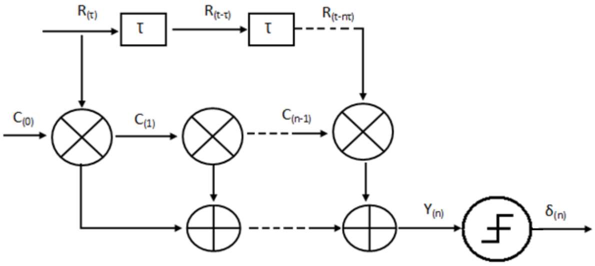

Fig 5. Feed Forward Equalizer

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 [55]. 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 in this equalizer [56]. An adaptive algorithm-based filter design is used to compensate for the dispersion in multimode fibers [56]. 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 [57]. Fig.6 shows the implementation of DWDM system using optical phase conjugation (OPC) block.

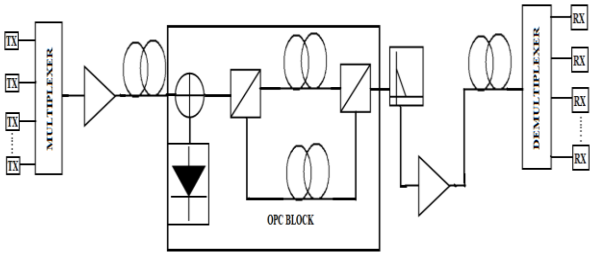

Fig6. WDM system design with OPC Block

5) Digital Filter

Digital filters with DSP algorithms are mainly designed for compensating 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 [57]. Other filters such as DPF, Gaussian, super-Gaussian, Butterworth, and microwave photonic filters are used [58]. Super-Gaussian filter, which can be a fully 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 [59]. Further, it will reduce dispersion and attenuation effects. This will lead to improved long-haul WDM system performance. FIR filters are used for compensating the polarization mode and chromatic dispersion. LMS algorithm-oriented system designs are more tolerant to chromatic dispersion and carrier phase noise than existing filters [32]. 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 1330nm & 1550nm. It has three different schemes with NRZ link through FBG compensator to achieve a high data rate in optical transmission [60]. Different modulation techniques are used for increasing the Q factor and for better eye-opening. Optical fiber is advisable for achieving huge 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 1310nm 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 [61].

a) Pre Dispersion Compensation Fiber Technique

Pre-dispersion compensation techniques involve placing the DCF either adjacent to the optical transmitter or before SMF for positive dispersion Compensation. In addition to dispersion, other losses are present in the transmitter signal [62]. Fig.7 shows the pre dispersion compensation design using 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.

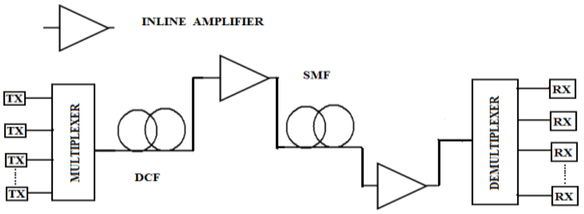

Fig 7: Pre dispersion Compensation system design

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 [63]. 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 DWDM system.

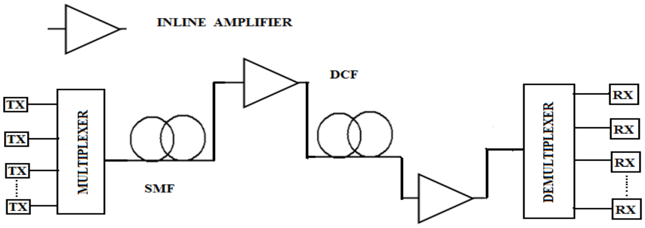

Fig 8. Post dispersion compensation system Design

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 an effective approach that reduces the bit error rate and enhances the performance of the proposed system [63]. 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.

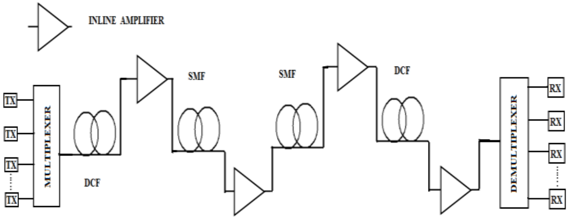

Fig 9: Combined compensation system design

4. COMPARISION SUMMARY

For years, various research methodologies have been proposed for dispersion compensation techniques. TABLE 1 shows the comparison summary of the researcher's contribution in this area. Each and every approach has its merits and demerits. The proposed lightpath design has specific requirements that are clearly based on the user requirements. Generally, the compensation technique that uses DCF is preferred due to its simple system design and ability to handle wider bandwidth demands.

TABLE 1. COMPARISON SUMMARY

Compensation Technique	***Merits***	***Demerits***
Dispersion management [21]	Inhibit FWM, average dispersion reaches to zero	Availability of Limited wavelength ranges, complex cable management
Un-equal channel spacing [64]	Low FWM crosstalk directly for few channel systems	Wider bandwidth, rigorous requirements on optical frequency Stability
Optical compensator [65] (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 [60]	Useful for future WDM system design.	Problem in fiber installation
Pre-compensation [66]	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 feedback system for transmission characteristics analysis
Post-compensation [62]	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 non-linearities 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 [33]	Provides broadband dispersion compensation simultaneously dispersion compensation	Limited bandwidth and data rate for transmission.
CFBG in Multichannel systems [67]	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 [62]	comprehensive solution Increased Accuracy User-based customization.	Complex structure Difficult to maintain
Symmetrical compensation mode [63]	Improved Signal Quality handle a wider range of application Most efficient compensation mode	Design and Implementation difficulties

5. PERFORMANCE MATRICS

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 utilized to predict the signal quality by monitoring the signal amplitude over the frequency and phase characteristics over a certain time [63]. 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 that degrade the lightpath performance. Spectral eye characteristics provide higher insights into both degradation characteristics and calculate the extinction ratio [68]. 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 [69]. 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 [70].

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 [71]. 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 require for achieving minimal BER [72]. 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 [73]. 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 received characteristics into 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 [74]. 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 number of channels [75]. For an adequate dispersion compensation, higher OSNR is necessary, along with receiver sensitivity criteria.

6. CONCLUSION AND FUTURE WORK

In Conclusion, this comparative study has discussed the dispersion compensation techniques in an optical communication system. In real-world scenarios, dispersion remains a challenging factor for deteriorating the quality of data transmission. However, this review elucidated the evolution, categorization, and analysis of active and passive dispersion compensation methods. It is also observed that the passive dispersion compensation techniques provide a cost-effective solution to mitigate the dispersion problems without introducing additional constraints. Active dispersion compensation methods can be adaptable to changing network conditions and well-suited for dynamic optical networking systems. The future scope of this review leads to extending the emergence of adaptive dispersion compensation techniques and machine learning-based approaches to changing the networking conditions in real-time for further enhancing the optical system performance.

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