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Various Dispersion Compensation Techniques for Optical System: A Survey

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Abstract:
Dispersion compensation is the most important feature required in optical fiber communication system because absence of it leads to pulse spreading that causes the output pulses to overlap. If an input pulse is caused to spread such that the rate of change of the input exceeds the dispersion limit of the fiber, the output data will become indiscernible. In this paper various dispersion compensation techniques are discussed like- Dispersion Compensating Fibers (DCF), Electronic Dispersion Compensation (EDC), Fiber Bragg Grating (FBG) and digital filters.

Keywords:
Digital filters; Dispersion; Dispersion Compensation; Dispersion Compensating Fibers (DCF); Electronic Dispersion Compensation (EDC); Equalizer; Fiber Bragg grating (FBG); Inter Symbol Interference (ISI); Optical Communication System

1. INTRODUCTION

Fiber optic communication is a method of transmitting information from one place to another by sending pulses of light trough optical fiber. The light forms an electromagnetic carrier wave that is modulated to carry information. The potential bandwidth of optical communication systems is the driving force behind the worldwide development and deployment of lightwave system.

Like other communication systems optical communication system also faces problems like dispersion, attenuation and non-linear effects that lead to deterioration in its performance. Among them dispersion affects the system the most and it is tougher to overcome it as compared to other two problems. Thus, it is important to work out an effective dispersion compensation technique that leads to performance enhancement of the optical system.

In this paper a survey of different compensation techniques has been presented.

2. DISPERSION

Dispersion is defined as pulse spreading in an optical fiber. As a pulse of light propagates through a fiber, elements such as numerical aperture, core diameter, refractive index profile, wavelength, and laser linewidth cause the pulse to broaden. Dispersion increases along the fiber length.

The overall effect of dispersion on the performance of a fiber optic system is known as Intersymbol

Interference (ISI). Intersymbol interference occurs when the pulse spreading caused by dispersion causes the output pulses of a system to overlap, rendering them undetectable [1].

Dispersion is generally divided into three categories: modal dispersion, chromatic dispersion and polarization mode dispersion.

2.1 Modal Dispersion

Modal dispersion is defined as pulse spreading caused by the time delay between lower-order modes and higher-order modes. Modal dispersion is problematic in multimode fiber, causing bandwidth limitation.

2.2 Chromatic Dispersion

Chromatic Dispersion (CD) is pulse spreading due to the fact that different wavelengths of light propagate at slightly different velocities through the fiber because the index of refraction of glass fiber is a wavelength-dependent quantity; different wavelengths propagate at different velocities.

Chromatic dispersion consists of two parts: material dispersion and waveguide dispersion.

2.2.1 Material Dispersion

It is due to the wavelength dependency on the index of refraction of glass i.e. refractive index of the core varies as a function of wavelength.

2.2.2 Waveguide Dispersion

It is due to the physical structure of the waveguide. In a simple step-index profile fiber, waveguide dispersion is not a major factor, but in fibers with more complex index profiles, waveguide dispersion can be more significant.

2.3 Polarization Mode Dispersion

Polarization Mode Dispersion (PMD) occurs due to birefringence along the length of the fiber that causes different polarization modes to travel at different speeds which will lead to rotation of polarization orientation along the fiber [2].

3. DISPERSION COMPENSATION TECHNIQUES

In order to remove the spreading of the optical or light pulses, the dispersion compensation is the most important feature required in optical fiber communication system.

The most commonly employed techniques for dispersion compensation are as follows:

3.1 Dispersion Compensating Fibers (DCF)

DCF is a loop of fiber having negative dispersion equal to the dispersion of the transmitting fiber. It can be inserted at either beginning (pre-compensation techniques) or end (post-compensation techniques) between two optical amplifiers. But it gives large footprint and insertion losses [3–5].

3.2 Electronic dispersion compensation (EDC)

Electronic equalization techniques are used in this method. Since there is direct detection at the receiver, linear distortions in the optical domain, e.g. chromatic dispersion, are translated into non linear distortions after optical-to-electrical conversion. It is due to this reason that the concept of nonlinear cancellation and nonlinear channel modeling is implemented. For this mainly feed forward equalizer (FFE) and decision feedback equalizers (DFE) structures are used. EDC slows down the speed of communication since it slows down the digital to analog conversion [3, 6, 7].

3.3 Fiber Bragg Grating (FBG)

Optical Fiber Bragg Grating (FBG) has recently found a practical application in compensation of dispersion-broadening in long-haul communication. In this, Chirped Fiber Grating (CFG) is preferred. CFG is a small all-fiber passive device with low insertion loss that is compatible with the transmission system and CFG's dispersion can be easily adjusted. CFG should be located in-line for optimum results. This is a preferred technique because of its advantages including small footprint, low insertion loss, dispersion slope compensation and negligible non-linear effects. But the architectures using FBG is complex [3, 8, 9].

3.4 Digital Filters

Digital filters using Digital Signal Processing (DSP) can be used for compensating the chromatic dispersion. They provide fixed as well as tunable dispersion compensation for wavelength division multiplexed system. Popularly used filter is lossless all-pass optical filters for fiber dispersion compensation, which can approximate any desired phase response while maintaining a constant, unity amplitude response [10, 11]. Other filters used for dispersion compensation are bandpass filter, Gaussian filters, Super-Gaussian filters, Butterworth filters and microwave photonic filter [12–14].

4. LITERATURE SURVEY

This study presented a survey of various performance enhancement techniques used in optical communication systems. It is seen that main drawback faced by fiber optics is dispersion which leads to broadening of the transmitted pulse. Many techniques have been developed and studied till date to compensate the dispersion:

4.1 Optical Fibers

First technique studied is the fiber itself whose characteristics can be tuned according to the requirements. Oldest one being Dispersion-Shifted Fibers (DSF) which was used to compensate dispersion at 1.55 μm wavelength i.e. zero dispersion wavelength [5]. But at this wavelength other effects such as Four Wave Mixing (FWM) and Cross Phase Mixing (XPM) were very high, therefore, Dispersion Compensating Fiber (DCF) was used having dispersion negative value equal to the transmitting fiber [3–5]. DCF can be used as pre-compensation, post compensation or in-line compensation fiber; but pre-compensation was preferred as it is robust to non linear phase noise [15]. Another such technique was Dispersion Managed (DM) cables or Reverse–Dispersion Fiber (RDF) based on mixing in each individual span a positive–dispersion fiber and a negative dispersion fiber that cancels overall dispersion and had the advantage of reducing the effects like FWM and XPM [5]. Also, this technique was lately used for dispersion compensation in Wave Division Multiplexing (WDM) systems which used Single Mode Fiber having large effective area and Bit Error Rate (BER) $\leq$ 10-9 was achieved [16].

4.2 Electronic Dispersion Compensation (EDC)

Electronic Dispersion Compensation (EDC) technique used electronics in optics for chromatic dispersion compensation [3]. Various methods are there for EDC. First one was producing a complementary PMD vector in the receiver to cancel the effects of first-order PMD in the fiber [17]. Most commonly used technique in EDC was use of equalization circuits. Hui Wu had proposed a design of integrated distributed transversal equalizers with focus on delay lines and gain stages which reduces the Intersymbol Interference (ISI) produced due to dispersion [7, 18]. D. E. Crivelli had investigated the combined adaptive digital equalization of all-order PMD, CD, and laser phase noise in high speed coherent optical transmission systems. Results showed that the new four dimensional equalizer can compensate channel dispersion of up to 1000 km of standard single-mode fiber [19]. Another EDC technique discussed was using an Asymmetric Mac-Zehnder Interferometer (AMZI) with a large Differential Time Delay (DTD). This process suppressed fiber nonlinearity and thermal noise [20]. MZI was also used as dispersion slope equalizer for the Spectra Amplitude Coding-Optical Code Division Multiple Access (SAC-OCDMA) system integrated with Arrayed-Waveguide Grating (AWG) router coder to improve the distortion in the system [21–23]. Dual-electrode Mach-Zehnder modulator and an Erbium-Doped Fiber Amplifier (EDFA) was also used to optimize the performances of radio on fiber (RoF) systems by enhancing SNDR of the system [**?**]. A. Gorshtein designed adaptive Least Mean Square (LMS) based equalizer that compensated CD and PMD. Output of the equalizer contained Intersymbol Interference (ISI) introduced by the Anti-Aliasing Filter (AAF) which was compensated using independent (non-linear) equalizer Maximum Likelihood Sequence Estimation (MLSE) [24]. D. Poe presented a Feed Forward Equalizer (FFE) with adjustable tap coefficients to reduce the effect of Inter-Symbol Interference (ISI) caused due to dispersion in optical fiber [25]. Also, I. Slim proposed Frequency-Domain (FD) Chromatic Dispersion (CD) compensation based on a non-maximally decimated Discrete Fourier Transform (DFT) filter bank with trivial prototype filters and a delayed single-tap equalizer per sub-band. For performance analysis, the required Optical Signal to Noise Ratio (OSNR) to tolerate different CD values at a BER of $10-3$ was chosen as the figure of merit [26]. Recently, A. S. Karar derived an electronic dispersion post-compensation algorithm for short reach optical links. Standard frequency domain equalization was performed to mitigate the link dispersion. The EDC algorithm improved the average BER and the average Error Vector Magnitude (EVM) [27]. J. Niu experimentally demonstrated an approach for broadband dispersion compensation. The simultaneous optical Phase Modulation (PM) and Intensity Modulation (IM) were implemented using a 2-Channel PM in conjunction with an optical polarizer that led to the broadband and long-reach dispersion compensation [28]. An adaptive filter along with an adaptive algorithm that controls the filter was used to compensate dispersion in a multimode fiber (MMF) transmission [29]. Combination of Orthogonal Frequency Division Multiplexing (OFDM) and Optical Single Sideband Modulation (OSSB) was also be used to adaptively compensate for chromatic dispersion in ultra-long-haul links. Advantage of OFDM is that by replacing dispersion compensating fibers with EDC, fewer optical amplifiers are required [6]. S. Tahvili demonstrated dispersion (pre) compensation for highly chirped optical pulses with an ultra compact optical pulse shaper in an InP-based generic integration platform. The control signals were optimized on the integrated pulse shaper, which compressed the optical pulses and a nearly flat chirp profile was obtained [30].

4.3 Fiber Braggs Gratings (FBG)

Nowadays completely optical components like Fiber Braggs Gratings (FBG) are used for chromatic dispersion compensation by recompression of the dispersed optical signal [3, 8]. M. Weiming demonstrated dispersion compensation over 50 km of standard single mode fiber (SMF) using chirped fiber grating (CFG) [31]. CFG is a small all-fiber passive device with low insertion loss that is compatible with the transmission system and CFG dispersion can be easily adjusted. CFG should be located in-line for optimum results [32]. Y. Aiying concluded that, the increased interaction of SPM and anomalous dispersion in CFG can be used to extend the transmission distance in point-to-point system [33]. M. J. Islam analyzed that FBG can also be used to compensate GVD, based on BER. The numerical results indicated that the BER performance can be improved significantly depending on the fiber length and chiprate [34]. Cascaded grating was implemented in WDM system to compensate GVD [35]. Chirped FBG (CFBG) is more preferred technique over LDF and DCF because of its advantages including small footprint, low insertion loss, dispersion slope compensation and negligible non-linear effects over others [9].

4.4 Digital Filter

As architecture of FBG is very complex so use of digital filters are preferred over it, especially for WDM. Digital filters when used along with digital signal processing can compensate chromatic dispersion [3]. Commonly used filter is lossless all-pass optical filters for fiber dispersion compensation, which can approximate any desired phase response while maintaining a constant, unity amplitude response [11]. M. H. Zadeh discussed two filters: bandpass filter and all pass filter for dispersion compensation in terms of Q-factor [14]. D. Enguang reported a WDM/CDMA optical fiber communication system with asynchronous despreading technology employing surface acoustic wave Minimum Shift Keying (MSK) match filter [36]. Y.J. He introduces super-Gaussian filters which can fully suppress phase jitter and greatly control the self frequency shift in ultrashort optical pulse. They are more effective than conventional filters, like Fabry Perot and Gaussian filters [37, 38]. Y.J. He also studied Butterworth filters for suppression of phase jitter. He proposed that both Butterworth filters and nonlinear gain for ultrashort solitons with higher-order effects can be used for this. Also Butterworth filters were suggested to replace conventional Gaussian filters to control phase jitter [39]. Also Super Gaussian filter and Fabry Perot filter removes the effects of the noise introduced by Semiconductor Optical Amplifiers (SOAs), Erbium Doped Fiber Amplifiers (EDFAs), and Raman optical amplifiers that lessen the effects of dispersion and attenuation allowing improved performance of long-haul optical systems [12]. Finite Impulse Response (FIR) filter can also be used to compensate polarization mode dispersion along with chromatic dispersion [40]. T. Xu compared three popular digital filters for chromatic dispersion compensation: a time-domain least mean square adaptive filter, a time-domain fiber dispersion finite impulse response filter, and a frequency-domain blind look-up filter. Results showed that LMS filter was most tolerant to the chromatic dispersion perturbation and the carrier phase noise than the other two filters [41]. B. Troia presented optical filters which gave wide free spectral ranges, as large as 12THz and low crosstalk, of the order of -20 dB [42]. Recent development in the use of filters for optical communication system is Microwave Photonics Filter [43–45]. R. K. Jeyachitra introduced a highly tunable spectrum sliced photonic microwave band pass transversal filter for microwave and millimeter wave frequency applications. The simulated result showed overall filter RF response with 18.28 GHz free spectral range, mainlobe to sidelobe suppression of 37.24 dB and Quality factor of 119 [13].

4.5 Digital Signal Processing

Major study in recnt time is to compensate dispersion based on Digital Signal Processing (DSP) without any use of dispersion compensator. This can be achieved in various ways. Firstly, optical time-domain Fractional Fourier Transform (FRFT) was proposed for dispersion free optical transmission. In this split-step Fourier integral method was used to simulate the combined effects of CD and SPM on the pulses propagation in fiber based on optical time-domain FRFT [46]. A. Yazgan examined Coherent Optical-Orthogonal Frequency Division Multiplexing (CO-OFDM) which was used to remove ISI caused by chromatic dispersion at long distances and high data rate [47]. Nonlinear Schrodinger Equation (NLSE) can also used to analyze the dispersion in the communication system. The combined effect of GVD and Self Phase Modulation (SPM) on the propagation pulses were analyzed through Nonlinear Schrodinger Equation (NLSE). Relative higher pulse energy induced phase shift proportional to the intensity and then created positive chirp, which was a linearly chirp in the center of the pulses. This linearly chirp cancelled the GVD induced broadening of the pulse partly, which finally lead to higher signal-to-noise ratios [48, 49]. Also, in coherent optical communication systems, no optical dispersion compensation is required. Here blind Chromatic Dispersion (CD) estimation technique was implemented using Lee's Timing Error Detector (TED) algorithm. Both BER and Peak-to-Average-Power Ratio (PAPR) were used to estimate the performance of the described technique [50, 51]. This method is most economical while having the same level of performance as all other methods as no additional circuit is required.

5. CONCLUSION AND FUTURE SCOPE

Fiber-optic communication because of its advantages over electrical transmission, have largely replaced copper wire communications in core networks in the developed world. But it is also marred by many drawbacks: dispersion, attenuation and non linear effect.

From this study it is clear that different researchers have used different techniques for dispersion compensation in optical system. In future work can be done in following directions:

1. Many researchers have presented different digital filters in the study for dispersion compensation but there is no comparative study among these. Therefore, a comparative study among these can be carried out.

2. **Gorshtein, A. and Sadot, D.** compensated dispersion with the use of DSP based equalizer using Least Mean Square Algorithm. The same process can be followed by using other algorithms like

Constant Modulus Algorithm (CMA) or Zero Forcing Algorithm (ZFA) [46] and the comparison among different techniques can be done.

3. **Cho, T. S. and Kwon, I. B.** optimized the performances of RoF systems in terms of Signal to Noise and Distortion Ratio (SNDR) with a dual-electrode Mach-Zehnder modulator and Erbium Doped Fiber Amplifiers including the third order Inter Modulation (IM3) and Amplified Spontaneous Emission (ASE) noise [41]. Optical noise at the transmitter was not considered in this study which can lead to decrease in SNDR, so further study can be done on this concept.

4. **Islam, M. J. and Islam, M. R.** proposed a Fiber Bragg Grating-based Group Velocity Dispersion (GVD) compensator but it is not able to overcome third order dispersion [35]. Therefore further study can be done to reduce third order dispersion.

5. **Xu, T., et al.** presented comparison among a time-domain LMS adaptive filter, a time-domain fiber dispersion FIR filter and a frequency-domain blind look-up filter to compensate the Chromatic Dispersion in an 112 Gbit/s NRZ-PDM-QPSK coherent optical transmission system [30]. Future efforts can be incorporated to compare the Chromatic Dispersion equalization performance of the three methods in the Return-to-Zero (RZ).

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