iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 6 **Issue:** II **Month of publication:** February 2018

DOI: http://doi.org/10.22214/ijraset.2018.2002

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor :6.887
Volume 6 Issue II, February 2018- Available at www.ijraset.com

Mathematical Modeling of LTI Impairments of Optical Coherent System Using Digital Signal Processing Techniques

Sunil Kumar Dahiya[1] Dr. Amit Kumar Garg[2]
[1]Ph. D. Research Scholar, DCR University of Science and Technology, ECED, Murthal (Sonepat)-India
[2]Professor, DCR University of Science and Technology, ECED, Murthal (Sonepat)-India

Abstract: Now-a-days optical fiber system based upon coherent detection for improving power and spectral efficiency. In digital coherent optical system, Linear Time invariant (LTI) and non-linear time invariant (Non-LTI) impairment are main factors which limits the transmission capacity and throughput. Chromatic dispersion and polarization mode dispersion are related to linear time invariant impairments, whereas Kerr nonlinearities and laser noise are related to Non-LTI impairments. Development and combination of coherent detection, multi-level modulation format and digital signal processor make the optical fiber communication system more efficient. DSP provide the ease compromising solution for mitigation of transmission impairments. DSP can be implemented at both transmitter (pre-compensation) and receiver (post compensation)to overcome the existing transmission impairments. In time domain approach, filtering input date is obtained by multiplication process rather than convolution process. FDE, high latency and complex multiplication and additions are the disadvantages, caused by FFT and IFFT. For large data, FIR filter is most efficient in frequency domain using either Overlap Add or Overlap Save method. Hybrid model of FDE/TDE is to be used for LTI impairments. In this paper, a novel mitigation technique based upon Digital signal processor (DSP) is proposed for linear transmission impairments and neglecting nonlinear impairments. CD is compensated in frequency domain and PMD is compensated in time domain due its time varying nature and also discuss the Comparison of different adaptive algorithms.
Keywords: Adaptive algorithm, LTI and DSP.

I. INTRODUCTION

In the early stage, dielectric waveguides was proposed by Kao and Hock ham in 1966. The first generation optical systems were commercially deployed in 1983 and which was operated in wavelength window of 800 nm over multimode optical fiber (MMF) at bit rate up to 45 Mbps. In the late 1970s the second generation of optical transmission systems were shifted to the second window of 1300 nm with standard single-mode fiber (SSMF), which offers much lower attenuation as compared to the previous 800 nm region and chromatic dispersion (CD) is near to zero. Optical system could operate at bit rates of up to 1.7 Gbps without the use of repeater upto distance 50 km. Introduction of coherent detection techniques could improve of the receiver sensitivity, and covered the distance 60 km without repeater with a bit rate of 2.5 Gbps. In third-generation, optical transmission systems operated on1550 nm wavelength window which has lowest-attenuation up to a bit rate of2.5 Gbps. In 1990, the optical transmission was based on direct modulation of the semiconductor laser source and direct detection since the introduction of erbium-doped fiber amplifier (EDFAs).Wavelength division multiplexing (WDM)systems that are capable of transmitting 10 Gbps channels with external optical modulators, which normally suffer an insertion loss of at least 3 dB. These modulators allow the preservation of the narrow line-width of distributed feedback lasers (DFBs). These high-speed and high-capacity systems extensively exploited the external modulation in their optical transmitters. The present optical transmission systems are considered as the fifth generation, having a transmission capacity of a few terabits per second. The development of coherent optical systems was to improve the receiver sensitivity nearly by 3–6 dB with transmission distance more than 60 km of SSMF. But, performance degraded in optical system was due to presence of fiber transmission impairments. In addition, the phase coherence for light-wave carriers of the laser source and the local laser oscillator were very difficult to maintain. On the contrary, the incoherent detection technique minimizes the line-width obstacles of the laser source as well as the local laser oscillator, and thus relaxes the requirement of the phase coherence. Moreover, incoherent detection mitigates the problem of polarization control in the mixing of transmitted optical signal and the local laser oscillator in the terahertz optical frequency range. The invention of EDFAs, which are capable of improving optical gains of 20 dB. The overall transmission capacity of WDM optical systems can be improved by increasing the transmission bit rate of each

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optical channel and multiplexing more channels in a DWDM system. The transmission capacity of optical system can be enhanced by increasing the number of multiplexed DWDM optical channels. This can be carried out by reducing the frequency spacing between these optical channels, from 100 GHz down to 50 GHz, or even 25 GHz and12.5 GHz. The reduction in the channel spacing also results in narrower bandwidths for the optical multiplexers and de-multiplexers. The narrowband filtering problems are becoming more severe at high data bit rates because signals are distorted due to inter-channel cross talk. After research and development has proved that coherent reception incorporating digital signal processing (DSP) can push the bit rates per wavelength channel to 100 Gbps by employing 25 GBaud polarization multiplexing and QPSK (two bits/symbol)and/or M-ary quadrature amplitude modulation (M-QAM) to aggregate to 200 Gbps or 400 Gbps. Furthermore, the channels can be made pulse shaped by using digital-to-analog converter (DAC) top ack the channels into super channels to generate terabits per second per channel with subcarriers. The advances of ultra-high sampling rate analog-to-digital converters (ADCs) and DACs at64 GSa/s allow the DSP to recover the clock, and hence the sampling rate and time, combating the linear and nonlinear impairments .The transmission for 100 Gbps would reach 3500 km in field trials and 1750 km for 200 Gbps over optically amplified and non-DCF fiber span transmission distances.

II. BACKGROUD AND RELATED WORK

Spectral efficiency can achieved 2.2 bit/s/Hz with 50GHz WDM system and 60% occupancy of spectrum. DSP is implemented at receiver, which equalized the chromatic dispersion in frequency domain. Both Residual CD and Polarization mode dispersion can compensated by the use butterfly structure of FIR filter. Complexity of equalizer depends upon the linearity present in fiber. ASE is generated by EDFA which limit the distance of optical transmission system. Dispersion compensation can be realized in the time domain using a finite impulse Response (FIR) filter, which has a non-recursive structure and can be implemented using a tapped delay line. Number of FIR taps grows linearly with accumulated dispersion, which results in high power consumption in long-haul systems. IIR filters are more computational efficient as compared to FIR filters but requires buffering. For systems with large accumulated dispersion, it would be more efficient to compensate for chromatic dispersion in the frequency domain using fast Fourier transforms (FFTs) rather than using time domain filters. Digital equalizer for compensation of chromatic dispersion CD and PMD in polarization multiplexed coherent optical systems. They found that the digital equalizer can fully compensate chromatic dispersion and first order PMD distortion, provided that the oversampling rate is at least 3/2 and sufficient number of equalizer taps are employed. The optimal tap settings are derived based on the minimum mean-square error (MMSE) criterion, which is shown to be a valid performance criterion despite the potential non-Gaussian of crosstalk and ISI [2]. DSP Compensation algorithms for LTI fiber impairments namely chromatic dispersion and polarization mode dispersion. DSP techniques provide highly flexible solutions for implementing impairments compensation and obtained an expression for frequency response of chromatic dispersion from which impulse response of the system can be calculated. Inverse Fourier transforms to be adopted for compensation. The main advantage of frequency domain approach is that the filtering of input data is obtained by multiplication process rather than convolution [4]. DP-QPSK coherent optical communication systems, post compensation DCF is one of the powerful means to mitigate dispersion, whereby in DP-16QAM dispersion compensation using DSP module can effectively compensate the dispersion [9]. Linear impairments are deterministic and have controllable impact on the performance of the transmission links in terms of BER, OSNR and Eye penalty. But nonlinear impairments have nondeterministic and partially controllable impact of the quality of transmission QoT of optical fiber transmission links. Besides the analytical modeling techniques an empirical modelling one which are based on numerical simulations or experimental results seems more promising especially for online impairment measurement and impairment compensation algorithms since empirical techniques will save more computational cost [7]. Sub-carriers multiplexed signals can improved the performance in long haul distance by using DSP and high speed DAC at Transmitter with BER limit of 3.8x $10^{-3}$for 24 Gbaud DP-QPSK transmission [12].

DSP can also be implemented at the both at the transmitter and receiver. The entire compensation and demodulation process can be done at the receiver, where adaptive processing may be considered in order to adjust for time-varying parameters in the link. Moreover, in order to take advantage of coherent detection, implementing DSP both side would be more costly and complex compared to receiver-side only DSP implementation. Pre-compensation is usually more efficient and better performing since pre-compensation acts on the transmitted signal before the noise is introduced by optical amplification and detection processes. The tradeoff between hybrid (pre and post) compensation and receiver-side only should be considered on a case-by-case basis. Clearly, the implementation of DSP in a real system cannot rely on offline processing as in most of the experimental demonstrations. Consideration of efficiency and computational load must be taken into account.

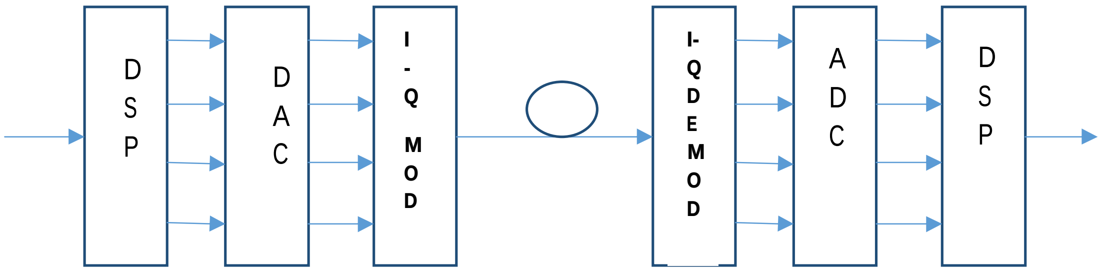

Figure 1: The Conceptual model of Coherent optical System

Figure 1 shows the conceptual model of Coherent optical system, Digital signal processor converts the input signal into In-phase and quadrature components of each two polarizations. Then, these four outputs of DSP is converted into analog form by DAC(digital to analog converter)and followed by Mach –Zehnderoptical modulators for electrical to optical conversion. The dually polarized signalis transmitted through optical channel. At Coherent receiver, signal are mixed with local oscillator and phase information can be detected by photodiode, convert the input optical signal into four electrical baseband signals i.e. In-phase and quadrature components of each two polarizations. All four outputs are digitalized by ADC (analog to digital converter) for DSP module, to yield the output. Phase estimation and polarization techniques are used for phase locking and polarization adjustment respectively. Bulk of Chromatic dispersion is compensated in frequency-domain equalizer and residual CD and PMD can be equalized by FIR filter (butterfly structure) based on blind or training based algorithms. The structure of this paper is as follows. In the section II model of LTI model of optical coherent system. In section III, review the compensation TDE and FDE, novel technique for mitigation of linear impairments on the basis of comparison.

III. LINEAR TIME INVARIANT MODEL OF COHERENT OPTICAL SYSTEM

One of the more fascinating possibilities of the use of DSP is the ability to compensate for both linear and nonlinear channel impairments. This technique allows an increase of several dBm in launching power, which translates to significantly improved performance, compared to linear compensation only. However, numerous repetitions of linear and nonlinear operations are required. This poses a great implementation challenge since power consumption, hardware complexity and latency are all at a premium. Moreover, the entire bandwidth which plays a role in the dispersion-nonlinearity interaction must be handled in parallel.

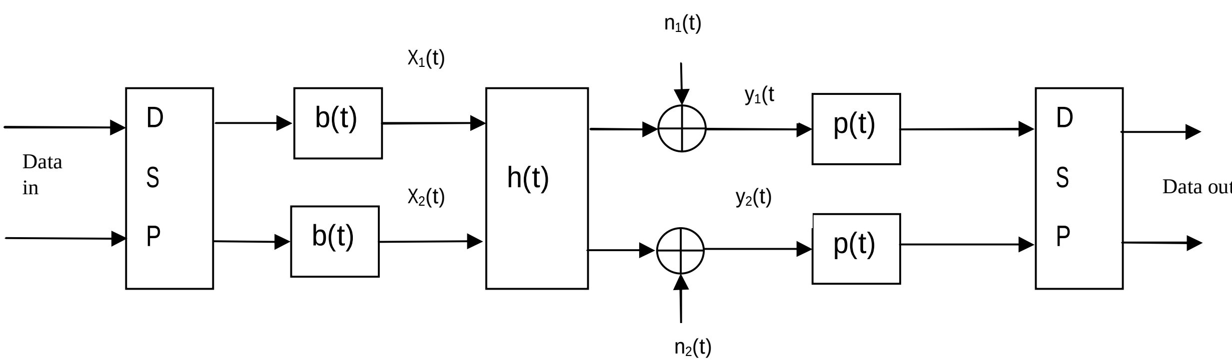

Figure 2: Linear Time Invariant (LTI) Model for Coherent Optical System (adapted from [2])

DSP is implemented at transmitter and receiver to mitigate the transmission impairments and act as pre and post compensator at input and output respectively. b(t) is the combined vector response of DAC, multiplexer and optical modulator, and p(t) is the combined vector response of photo-receiver, de-multiplexer and ADC. n(t) is noise response and h(t) is channel response. $x(t)=[x_1(t)\ \ x_2(t)]^T$ and $y(t)=[y_1(t)\ y_2(t)]^T$ are the baseband, analog electric field at transmitter and receiver respectively, whose components are complex valued i.e. Real as I and imaginary part as Q of respective polarizations.

$y(t)= h(t) \otimes x(t) + n(t)$

After Fourier Transformation, then

$Y(\omega)= H(\omega)\ X(\omega) + N(\omega)$

Propagating field in long haul single mode fiber is described as consisting of two degenerate modes each corresponding to two orthogonal polarizations. The degeneration is introduced due to the cylindrical symmetries of the optical fiber. Generally optical fibers has physical structure that is not perfectly cylindrical that leads to imperfection and perturbation due to mechanical tension, thermal gradients etc. Due to these imperfections the two fundamental modes see different indices of refraction in the fiber. The two polarization modes are propagating with slightly different group velocity. This phenomenon is called polarization mode dispersion (PMD). H(ω) is total frequency response of channel, N(ω) is equivalent noise vector. Equalization algorithm for linear impairments, the channel model is

$H(\omega) = H_{CD}(\omega)\ H_{PMD}(\omega)$

Dual Polarization Nonlinear Schrodinger Equation of Signal propagation

Signal propagation through optical fiber is described by non Linear Schrödinger Equation (NLSE), where β can be expanded around the carrier frequency into a Taylor series approximation, truncated at the 3rd term.

$$\frac{\partial E}{\partial z} = \left(-\frac{1}{2}\alpha - \beta_1\frac{\partial}{\partial t} - \frac{1}{2}\beta_2\frac{\partial^2}{\partial t^2} + \frac{1}{6}\beta_3\frac{\partial^3}{\partial t^3}\right)E + j\Upsilon\left[|E|^2 I - \frac{1}{3}(E^H\sigma_3 E)\sigma_3\right]E \qquad (1)$$

$$\widehat{D} = \left(-\frac{1}{2}\alpha - \beta_1\frac{\partial}{\partial t} - \frac{1}{2}\beta_2\frac{\partial^2}{\partial t^2} + \frac{1}{6}\beta_3\frac{\partial^3}{\partial t^3}\right)E \qquad (2)$$

$$\widehat{N} = j\Upsilon\left[|E|^2 I - \frac{1}{3}(E^H\sigma_3 E)\sigma_3\right]E \qquad (3)$$

$$\frac{\partial E}{\partial z} = \left(\widehat{D} + \widehat{N}\right)E \qquad (4)$$

If Nonlinearities is ignore i.e. $\Upsilon=0$,

$$\frac{\partial E}{\partial z} = \left(-\frac{1}{2}\alpha - \beta_1\frac{\partial}{\partial t} - \frac{1}{2}\beta_2\frac{\partial^2}{\partial t^2} + \frac{1}{6}\beta_3\frac{\partial^3}{\partial t^3}\right)E \qquad (5)$$

or

$$\frac{\partial E}{\partial z} = \widehat{D}E \qquad (6)$$

By solving analytically the NLSE with only the GVD term, one will find that CD is accurately modeled as an all-pass linear filter whose frequency response is given by

$H_{cd}(\omega, z) = \exp(-j\ \beta_2\omega^2 z/2)$

where, ω is the angular frequency, $\beta 2 = \beta 2(\omega_c)$ is the GVD parameter at the carrier angular frequency ω_c, and z is the propagated distance. The dispersion parameter D at a given wavelength is often specified instead of $\beta 2$. The relation between both is given by

$D = -2\pi c\ \beta_2/\ \lambda^2$

where, c is the speed of light in vacuum and λ is the wavelength. The parameter D is usually given in $ps/(km \cdot nm)$. In optical communication systems, the temporal broadening of the pulses caused by CD translates in ISI, which will degrade the system performance if not compensated.

α is attenuation or fiber loss, β_1 is group velocity, β_2 is dispersion, β_3 is dispersion slope and γ is coefficient of nonlinearity.

α , β_2 and β_3 are negligible dependent to polarization. Two polarization propagate along the fiber at group velocity and describe as

$$\beta_1(z) = \beta_1 = R(\theta,\phi)\left(\frac{\delta}{2}\right)R^H(\theta,\phi) \qquad (7)$$

$R^H(\theta,\phi)$is rotation matrix and columns of rotation matrix are jones vectors of polarization. δ is DGD(differential group delay) per unit length. (β_2L) is the residual chromatic dispersion and PMD is limits to first order. Chromatic dispersion affects equally both polarizations. PMD which leads to relative delays between the two principal states of polarizations.

IV. LTI IMPAIRMENTS COMPENSATION TECHNIQUES

LTI impairments are described by unitary matrices in frequency domain and these are compensated by linear equalizer. Selection of

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ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor :6.887
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Linear equalizer are depends upon modulation format and ISI duration. Linear equalizer should be adaptive which track the error according and PMD is time varying in nature. Error is difference between desired signal and output of equalizer after processing of received samples.

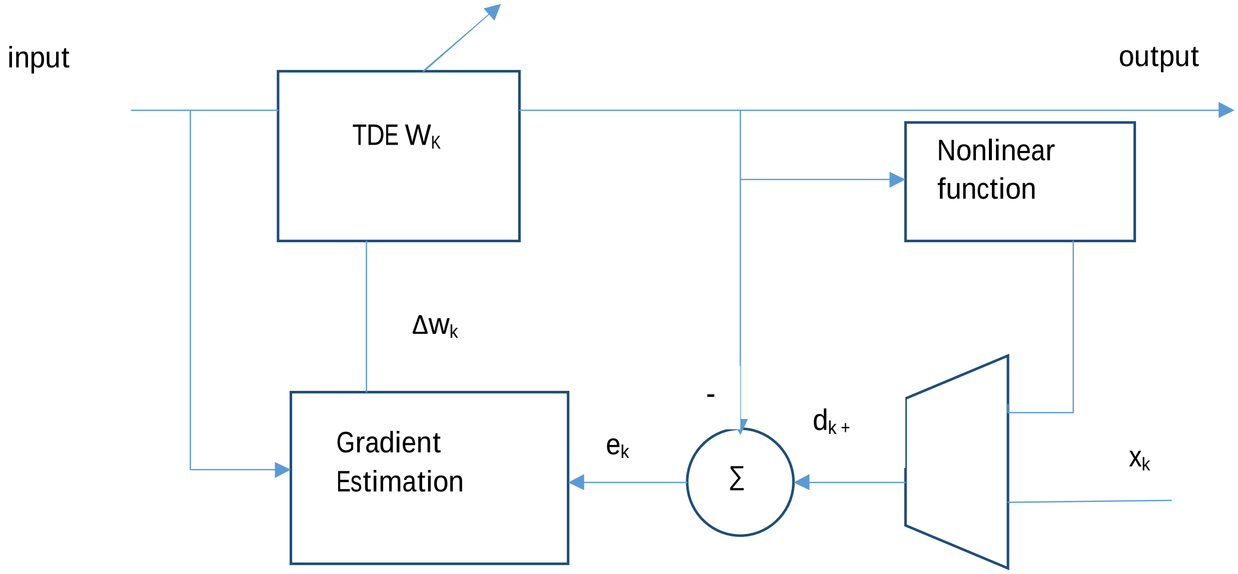

Figure 3: Adaptive TDE Model

In time domain, taps of linear equalizer are adjusted as in response of error through the gradient estimation, which help to minimize the cost function. In decision aided algorithm, error is find between training symbols and output of linear equalizer. Use of training symbols may have synchronize problem when initialized. Hence it is not suitable. Whereas decision directive, training symbols are considered as correct and error is equalizer output and decided symbols. If the training symbols are missed then, it is known as blind adaptive algorithm. Godard was introduced a cost function for phase modulated constellation, in which cost function is computed for target radius and is known as radius –directive algorithm. Constant modulus algorithm is type of radius directive algorithm provided fixed value of integer i.e. 2 and it is computed to minimize the cost function for each polarization. Godard algorithm works for both constant and non-constant modulus constellation.

Coefficients of linear equalizer are modified in response of exact gradient function and rate of convergence is depend upon the step size. If step size is large, then, rate of convergence will be fast which leads to diverge the coefficient i.e. mis-adjustment. So that it is very difficult to find the exact gradient function. Least mean square algorithm provide the single shot solution to estimate the gradient. Cost of adaption for every symbol in equalizer with LMS algorithm is 100%.

Recursive Least Square (RLS) Algorithm has fast rate of convergence as compare to LMS and computed for close to accurate estimate the gradient, which is updated recursively after every symbol. RLS is more complex than LMS due to calculation of inverse matrix and is not good for implementation in optical transmission system at higher bit rate.

Table 1: Difference between LMS and RLS Algorithm

Sr No	LMS (Least Mean Square) Algorithm	RLS (Recursive Least Square)Algorithm
1	Low speed of convergence	High speed of convergence
2	No. of iteration is high	No. of iteration is less
3	Need extra command to control	Highly controllable
4	Simple and easy to implement	Complex to implement
5	Low SNR	High SNR
6	Small tracking error	High compare to LMS
7	Superior performance at narrow band signals	High performance for signal bandwidth

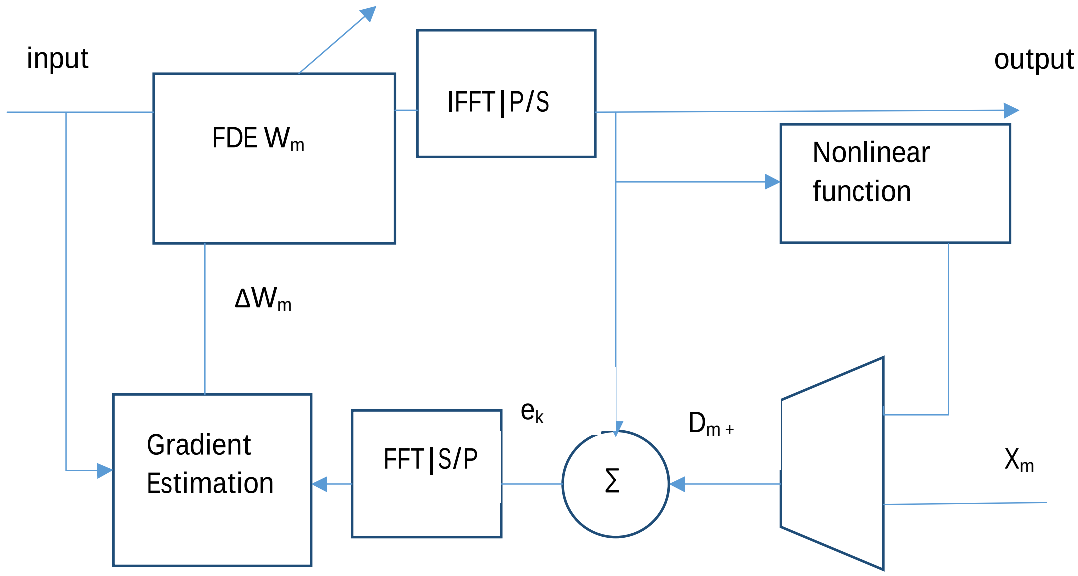

Figure 4: Adaptive FDE Model

In frequency domain, computation cost is reduced with introduction of FFT and IFFT and complexity increases. Feedback delay is major disadvantage in frequency domain due to presence of FFT and IFFT block in feedback loop. Time constant for adaptive FDE is longer than adaptive TDE.

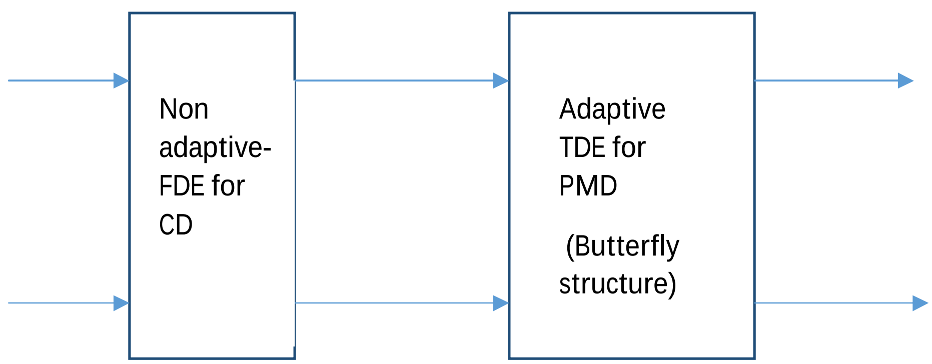

Figure 5: Hybrid FDE-TDE structure for compensating CD and PMD

In the hybrid structure which consists of non-adaptive FDE block for chromatic dispersion which is suitable due static and adaptive TDE block for compensation of time varying PMD.TDE has least latency as compare to FDE. Hence, hybrid FDE-TDE structure improve performance of equalizer. The length of adaptive TDE is lies between 7 to 13 taps and adaptive FDE is depends upon residual dispersion.

Table 2: TDE and FDE

	Processing requirements (Multiplication per symbols)	Feedback latency (of multiplications)
Time – Domain Equalizer (TDE)	O(N)	O(1)
Frequency – Domain Equalizer (FDE)	O($\log_2$N)	O($\log_2$N)

An FDE, size of FFT and IFFT are 2N/B, FFT is reduced by $\log_2$B for each stages of Butterfly structure and leads to shorter latency delay. The computational cost increases as the number of FFT and IFFT operations.

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Table 3: Comparison between FIR and IIR Filter

Sr . No.	FIR Digital filter	IIR Digital Filter
1.	FIR system has finite duration unit sample. h(n)=0 for n<0 and n>=M i.e. duration from 0 to M-1	IIR system has infinite duration unit sample. h(n)=0 for n<0 i.e. duration from 0 to infinite
2.	Output of FIR system depends upon present and past inputs.	Output of IIR system depends upon present and past inputs as well as past outputs.
3.	They are non-recursive in nature.	They are recursive in nature and use the feedback.
4.	FIR systems has limited or finite memory requirements.	IIR system requires infinite memory.
5.	FIR filter are always stable.	Stability cannot be always guaranteed.
6.	FIR filter has exactly linear phase response.	IIR filter usually more efficient design in terms of computation time and memory requirements. It requires less processing time and storage as compared with FIR.
7.	All zero filters.	Poles and Zeros are present.
8.	The effect of using finite word length to implement filter. Noise and quantisation error are less severe in FIR as compare to IIR.	Analogue filter can be easily converted to IIR filter.
9	FIR filter is used where no phase distortion is required.	IIR filter is used where sharp cut-off and high throughput is required.

The symbol rate of T, finite impulse response (FIR) filter may be used T/2 tap delays to reverse the effect of fiber chromatic dispersion. The number of FIR taps required grows linearly with increasing dispersion. An alternative to FIR filtering, IIR filters inherently require a reduced number of taps for a similar response compared to their FIR counterparts due to the feedback path.

Table 4: Mitigation Techniques for Linear Transmission Impairments

Sr. No.	Transmission impairments	Techniques
1	Chromatic dispersion	1. Time domain- LMS adaptive filter. 2. Frequency domain- Finite impulse response(FIR) 3. Frequency domain equalizer (FDE)
2	Polarization Mode dispersion	In time domain 1. LMS(Least Mean Square) 2. CMA(constant Modulus Algorithm) 3. RLS (Recursive Least Square)
3	Laser phase noise	Carrier Phase Estimation(feed –forward and feed-back) 1. One- Tap normalize LMS 2. Differential Phase estimation 3. Block –wise average 4. Viterbi- Viterbi method
4	Dispersion and Kerr's nonlinearities	Back propagation(Digital and Optical)

V. RESULTS AND DISCUSSIONS

DSP has capability to split, amplify and manipulate the signal without degradation of Signal quality.DSP algorithm becomes complex as the increases the bit rate, constellation size and Transmission distance. In time domain approach, filtering input update is obtained by multiplication process rather than convolution process.FDE, high latency and complex multiplication and additions are the disadvantages, caused by FFT and IFFT. For large data, FIR filter is most efficient in frequency domain using either Overlap Add or Overlap Save method. Hybrid model of FDE/TDE is to be used for LTI impairments.CD and PMD compensation can be done effectively with FDE and TDE respectively.PMD compensation can be done after CD compensation. Single high speed carrier splits into low rate sub-carriers and nonlinearity tolerance improves by optimizing the numbers of sub-carriers. Low speed sub-carriers multiplexing is done with use of DSP.

Transmission in the linear regime (with low total optical powers) avoids degrading nonlinear effects, yet dispersion compensation must still be considered. In the digital domain finite-impulse-response (FIR) filtering can be used for this purpose. However, infinite-impulse response filters are more efficient since these incorporate a feed-back path. Real-coefficients IIR filters for chromatic dispersion compensation may achieve savings of close to 1.7 in number of operations required for dispersion compensation compared to FIR filters. The reason for the limited savings in computational load is that there is a large overhead at short transmission distances. The added complexity associated with real, all-pass IIR filtering for dispersion compensation is to be considered as a tradeoff with the savings in number of operations

VI. CONCLUSIONS & SCOPE FOR FUTURE WORK

DPS provide the compromising solution to transmission impairments. When the light propagate through fiber, it experiences channel transmission impairments which are plays the major to limit the capacity and throughput due to physical geometry of optical fiber. Chromatic dispersion is static whereas PMD is time varying in nature. CD is fully compensated in frequency domain and PMD is mitigated in time domain. PMD compensation block placed after the CD compensation block at receiver end. Infinite impulse response (IIR) filtering for chromatic dispersion compensation is considered as an alternative to FIR filtering. IIR filters inherently require a reduced number of taps for a similar response compared to their FIR counterparts due to the feedback path. Hybrid FDE-TDE structure is used for compensation of chromatic dispersion and PMD with cost function efficient and latency. Nonlinear fiber impairments compensation techniques using advance DSP, advance modulation formats and high speed ADC/DAC in coherent optical system will be the scope for future work.

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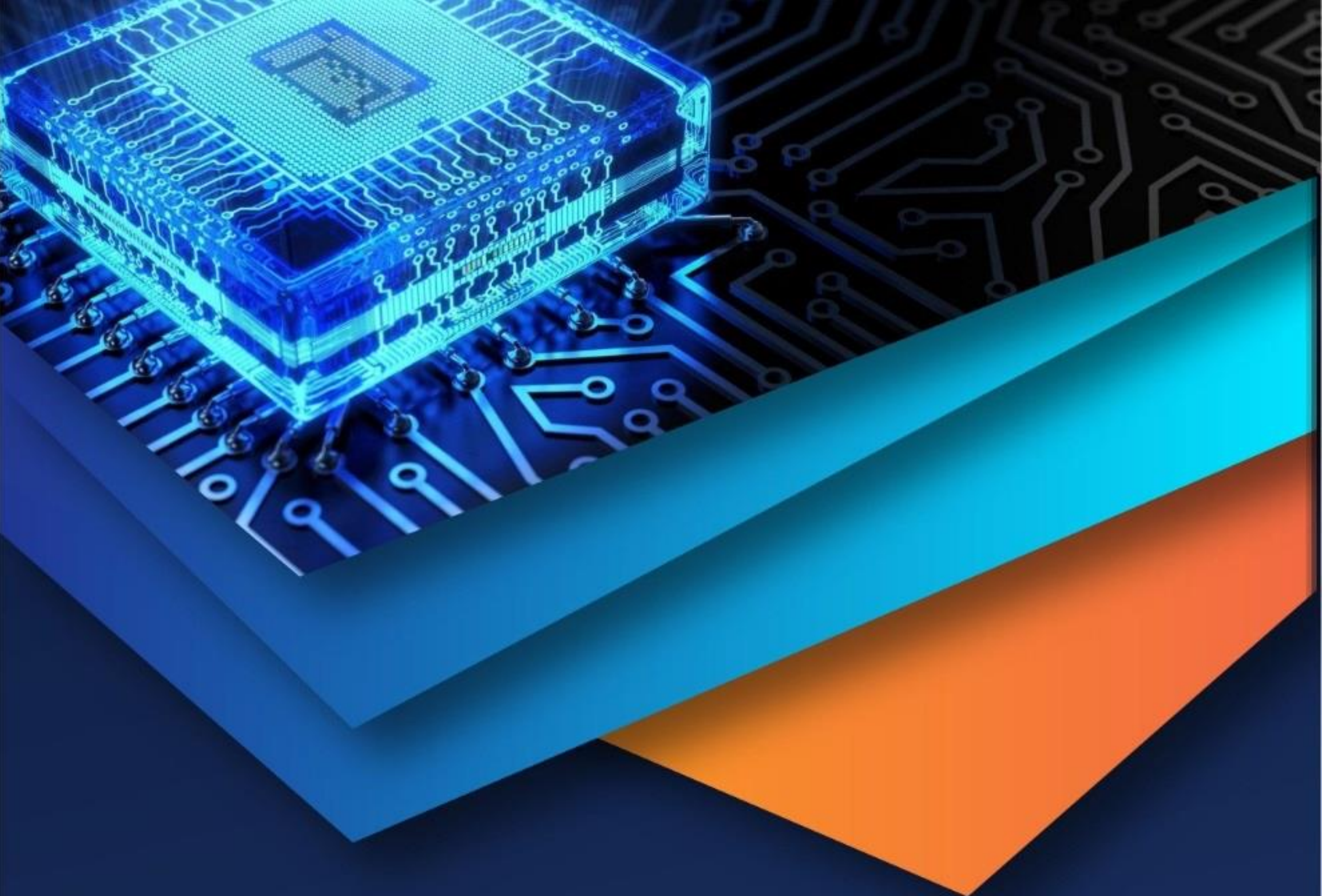

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