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Chromatic Dispersion Mitigation in Single Carrier High Speed Coherent Optical Communication Using Digital Signal Processing Techniques

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ABSTRACT

Optical fiber networks have been emerged to be the backbone of global communication infrastructure in present world. But, they are currently experiencing an unprecedented level of stress in order to meet the demand of increasing bandwidth-hungry applications. Moreover signals are frequently subjected to distortion due to optical fiber impairments while being propagating through a fiber optic cable. This paper demonstrates digital signal processing (DSP) based chromatic dispersion (CD) estimation and mitigation technique for single carrier high speed coherent optical communications. Coherent detection permits the optical field parameters (amplitude, phase and polarization) to be available in the electrical domain enabling new opportunity for multi-level signaling (M-ary PSK and M-ary QAM modulation). That is why Coherent detection employing QAM modulation formats have become one of the most promising technologies for next generation high speed transmission systems due to the high power and spectral efficiencies. In recent days, the realizations of DSP algorithms for estimating and mitigating the chromatic dispersion in the coherent transmission systems are the most attractive investigations. In this paper, CD estimation technique has been improved using DSP algorithm and optimal OSNR, BER have been achieved.

Keywords – chromatic dispersion (CD), coherent detection, digital signal processing (DSP), PSK, QAM.

I. INTRODUCTION

In order to cope with the increasing global information exchange it's becoming crucial to transmit information over longer distance. A solution to this issue is optical fibers that are already used for most of the voice and data traffic all over the world. Optical fibers are exceptionally advantageous for long-haul communication systems.

The reason behind it, when light propagates through an optical fiber it suffers from less attenuation than the case of an electrical cable. Moreover it's possible to transmit several channels, at different wavelength, on the same medium using wavelength division multiplexing (WDM). This enables to reach a capacity system of several Tbps. Recently, digital coherent optical communication has become the main technology for optical transport networks [1]. Moreover, digital signal processing is under consideration as a promising technique for optical signal modulation, fiber transmission, signal detection and dispersion compensation. There are different reasons why the utilization of coherent detection associated digital signal processing can be very advantageous. Firstly, coherent detection is a promising technology to increase optical receiver sensitivity, permitting a greater span loss to be tolerated. Secondly, coherent detection enables supporting of more spectrally efficient modulation formats such as quadrature phase shift keying (QPSK) and quadrature amplitude modulation (QAM). And finally, instead of implementing costly physical impairments compensation links, coherent detection allows digital signal processing for compensation of transmission impairments such as CD, polarization mode dispersion (PMD), signal carrier offset, spectrum narrowing etc. Furthermore, next generation optical transmission systems require adaptive fitting for time varying transmission impairments such as channel spectrum narrowing and random phase noise. Digital signal processing is a powerful solution for future adaptive optical transmission links.

Recently, 100-Gb/s technologies using polarization-division-multiplexed quadrature-phase-shift-keying (PDM-QPSK) and digital coherent detection have been commercialized, and the focus of the optical communication industry is moving beyond 100-Gb/s. In a digital coherent optical communication system, no optical dispersion compensation is required and the large amount of chromatic CD accumulated along the link can be compensated by DSP in a coherent optical receiver [2]. As there occurs large amount of accumulated CD in the system, a relative small error in CD estimation and compensation can cause failure of subsequent clock recovery, dynamic butterfly equalizer and carrier recovery, and thus entire digital detection process of the receiver. Moreover, CD is mainly responsible for pulse broadening which gives birth to bit error rate (BER). Therefore, accuracy in CD estimation and compensation are requisite for a coherent optical receiver [3].

II. HISTORICAL PERSPECTIVES

Coherent optical fiber communications were studied extensively in the 1980s mainly because high sensitivity of coherent receivers could elongate the unrepeated transmission distance. However, their research and development have been interrupted for nearly 20 years behind the rapid progress in high-capacity wavelength-division multiplexed (WDM) systems using erbium-doped fiber amplifiers (EDFAs). In 2005, the demonstration of digital carrier phase estimation in coherent receivers has stimulated a widespread interest in coherent optical communications again. This is due to the fact that the digital coherent receiver enables us to employ a variety of spectrally efficient modulation formats such as M-ary phase-shift keying (PSK) and quadrature amplitude modulation (QAM) without relying upon a rather complicated optical phase-locked loop. In addition, since the phase information is preserved after detection, we can realize electrical post-processing functions such as compensation for chromatic dispersion and polarization-mode dispersion in the digital domain. These advantages of the born-again coherent receiver have enormous potential for innovating existing optical communication systems.

III. ASSIMILATING DIFFERENT CD ESTIMATION METHOD

Many methods for CD estimation have been proposed and demonstrated [4]. A commonly adopted solution is the using Dispersion-Compensating Fiber (DCF). However DCF introduces additional loss, therefore requiring additional optical amplifiers increasing additional noise and cost of the system. An alternative approach is to compensate entirely CD in the electric domain. At the very beginning, equalization with training sequence was used but this method is found to be good only for low dispersion system, as any system has a relative high CD in practice, or system with DCF and residual CD. The mean advantages of utilizing coherent detection with DSP algorithms can be summarized as follows. Firstly, coherent detection with DSP algorithms is able to detect advanced modulation formats with improved spectral efficiency, such as n-phase-shift keying (PSK). Secondly, coherent detection with DSP algorithms provides potential for superior receiver sensitivity. Furthermore, coherent detection with DSP algorithms enables electrical offline compensation for impairments arising due to fiber transmission [5]. Coherent detection with DSP algorithms can take advantage from continuously increasing electrical processing speed. Moreover optical coherent detection can benefit from intensive researches concerning digital signal processing algorithms. Consequently, it is efficient and simple to implement optical signal processing in digital domain.

IV. PROPOSED MODEL

The aim of this research is to develop and analyze digital signal processing techniques for enhancing performance in coherent optical communication systems. This scheme allows the use of PDM without the need for adaptive optics, and also enables full compensation of arbitrary amounts of previously limiting effects such as PMD and CD. This DSP method allows us to reduce the Polarization mode dispersion, Chromatic dispersion. By implementing this DSP algorithm it is possible to achieve high data rate communication applications.

V. THEORETICAL OVERVIEW

In coherent detection systems, a complex modulated signal, whose information lies not only on its amplitude but phase as well, can be written as:

$$E_S(t) = A_S(t)\,exp[i(\omega_S t + \phi_S)] \qquad (1)$$

Where ω_S and ϕ_S are the signal's carrier frequency and time dependent phase variable, and $A_S(t)$ is the amplitude component of the signal. The optical field associated with the local oscillator (LO) can be written as:

$$E_{LO}(t) = A_{LO}(t)\,exp[i(\omega_{LO} t + \phi_{LO})] \qquad (2)$$

Where ω_{LO}, $A_{LO}(t)$ and ϕ_{LO} are respectively the carrier frequency, amplitude and time dependent phase variable of the LO. The scalar notation is used for both $E_S(t)$ and $E_{LO}(t)$ due to assuming that two fields are identically polarized [6].

There are different coherent detection schematics to cope with the coherent detection technique denoted as single coherent detection with single photodiode (PD), single coherent detection with balanced-photodiode (B-PD), quadrature coherent detection with 90◦-hybrid and dual polarization coherent detection.

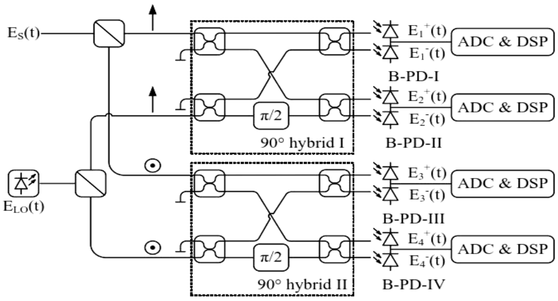

Fig 1. Dual polarization coherent detection with balanced PD

International telecommunication union (ITU) defined criteria as, channel spacing of 100 Gb/s optical communication systems is assigned to be 50 GHz. In order to fulfill such bandwidth requirements, dual polarization coherent detection with balanced PD will better option. As it is explored by several researches [7-8], polarization diversity is under consideration as the third degree of modulation freedom. As two of in-phase and quadrature modulation formats are capable for any level complex modulation then dual polarization will further double the capacity of transmission systems [9]. For instance, 28 Gbaud electrical pseudo random binary sequence (PRBS) can drive 56 Gb/s optical QPSK signals using 30 GHz bandwidth Mach-Zehnder modulator (MZM). Using dual polarization modulation, entire system bit rate will be increased to 112 Gb/s. Instead of using scale number of 100 Gb/s for practical optical communication systems, 112 Gb/s systems are suitable for taking forward error correction (FEC) sequences into account [10].

VI. TECHNICAL DESCRIPTION

The common configuration of optical coherent receiver associated with DSP algorithms is shown in Fig. 3. Coherent detection with DSP algorithms can take advantage from continuously increasing electrical processing speed. Consequently, it is efficient and simple to implement optical signal processing in digital domain. Four main functions are performed in digital domain: 1) Dispersion compensation, 2) Clock recovery, 3) Polarization de-multiplexing, and 4) Carrier phase estimation.

6.1 Dispersion Compensation

The frequency response for an all-pass filter to compensate fiber CD can be expressed as in the absence of fiber nonlinearity:

$$G(z,\omega)=\exp[-jD\frac{\lambda^2}{2\pi c}\frac{\omega^2}{2}z+jS\left(\frac{\lambda^2}{2\pi c}\right)^2\frac{\omega^3}{6}z] \qquad (3)$$

Where D is the dispersion coefficient, S is the dispersion slop, ω is the angular frequency, λ is the light wavelength, c is the light velocity, and z is the fiber length. In order to compensate for the dispersion, the output field is multiplied to the inverse of the channel transfer function (FIR filter) [11]. After CD compensation at frequency domain, IFFT inverts the sequence back to the time domain.

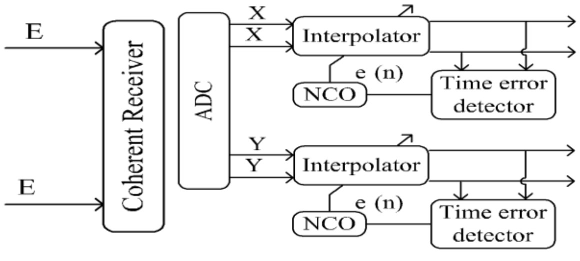

Fig 2. Structure of Gardner clock recovery DSP algorithm

6.2 Clock Recovery

In general, any sampling clock errors significantly reduce system BER performance. Therefore clock recovery DSP algorithm is demanded to determine the suitable sampling clock. The clock recovery DSP algorithm implemented in this paper is known as Gardner algorithm [12], which is widely used in the field of wireless communication systems. Structure of Gardner clock recovery is shown in Fig. 2.

The numerically controlled oscillator (NCO) is driven by outputs from Gardner time error detector $e_x(n)$ and $e_y(n)$, which are defined in equation 2 and equation 3.

$$\begin{aligned} e_x(n) &= X_I(n)[X_I(n+1)-X_I(n-1)]+ \\ &\quad X_Q(n)[X_Q(n+1)-X_Q(n-1)] \end{aligned} \qquad (4)$$

$$\begin{aligned} e_y(n) &= Y_I(n)[Y_I(n+1)-Y_I(n-1)]+ \\ &\quad Y_Q(n)[Y_Q(n+1)-Y_Q(n-1)] \end{aligned} \qquad (5)$$

Where n-th element of time error represents difference between two adjacent samples from ADC. Sample period is equal to $T_S/2$, where T_S is symbol period of transmitted signal. The implementation of interpolator is used to interpolate adjacent symbols with new sampling clock. The mean purpose of Gardner clock recovery algorithm is to sample the adjacent sequences with the same time difference that $e_x(n)$ and $e_y(n)$ are equal to zero.

6.3 Polarization Demultiplexing

In order to emulate the cross-talk between the signals carried on two polarizations, Jones matrix is employed, which is given as:

$$\begin{pmatrix} \sqrt{\alpha e^{i\delta}} & -\sqrt{1-\alpha} \\ \sqrt{1-\alpha} & \sqrt{\alpha e^{-i\delta}} \end{pmatrix} \qquad (6)$$

Where α and δ denote the power splitting ratio and phase difference between two polarizations. Therefore the polarization multiplexed signal at the receiver side after fiber propagation can be presented as [13].

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix}=\begin{pmatrix} \sqrt{\alpha e^{i\delta}} & -\sqrt{1-\alpha} \\ \sqrt{1-\alpha} & \sqrt{\alpha e^{-i\delta}} \end{pmatrix}\begin{bmatrix} E_{in,x} \\ E_{in,y} \end{bmatrix} \qquad (7)$$

So if the inverse of Jones matrix is found, polarization de-multiplexing can be performed.

$$\begin{bmatrix} E_X \\ E_Y \end{bmatrix}=\begin{pmatrix} P_{xx} & P_{xy} \\ P_{yx} & P_{yy} \end{pmatrix}\begin{bmatrix} E_x \\ E_y \end{bmatrix} \qquad (8)$$

The matrix elements are updated symbol by symbol according to

$$P_{xx}(n+1)=P_{xx}(n)+\mu(1-|E_x(n)|^2)E_x(n)E_x^*(n) \qquad (9)$$

$$P_{xy}(n+1)=P_{xy}(n)+\mu(1-|E_x(n)|^2)E_x(n)E_y^*(n) \qquad (10)$$

μ is the step-size parameter and n is the number of symbols. The P matrix is basically an adaptive FIR filter and we use CMA for blind estimation [14]. The initial values for $P_{xx}(0)$ and $P_{yy}(0)$ are: $P_{xx}(0)$ = [00…010..00];$P_{yy}(0)$ = [00…010..00];again $P_{xy}(0)$=$P_{yx}(0)$= [00…000..00]. In this simulation a 3-tap FIR filter, however the order can be changed is chosen.

6.4 Carrier phase estimation

Phase locking in the hardware domain can be replaced by phase estimation in digital domain by DSP [15]. The received QPSK signal can be presented to estimate the phase of the signal in digital domain by:

$$E(t) = A\exp\{j[\theta_S(t)+\theta_C(t)]\} \qquad (11)$$

VII. SYSTEM DESIGN

The configuration of optical coherent receiver associated with DSP algorithms is shown in Figure. In this block diagram, several DSP algorithms are under consideration. CD compensation block is used to compensate for chromatic dispersion. Clock recovery block is implemented to correct digital sampling error which is made by analog to digital converters (ADC). Polarization de-multiplexing is realized by using polarization de-multiplex algorithm. Phase and frequency offset recovery block is employed to correct phase and frequency difference between received signal and Local Oscillator.

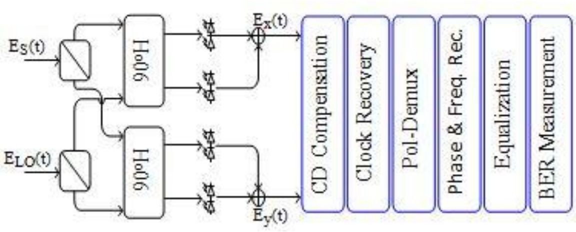

Fig 3. Configuration of coherent detection with DSP

VIII. SIMULATION DESCRIPTION

In this subsection, the combination of coherent detection with DSP algorithm is proposed to compensate for CD in dual polarization (DP) QPSK systems. The configuration diagram of optical DP-QPSK system with coherent digital receiver is shown in Fig. 4.

The 100 Gbps DP-QPSK system can be divided into five main parts: DP-QPSK Transmitter, Transmission Link, Coherent Receiver, Digital Signal Processing, and Detection & Decoding (which is followed by direct-error-counting). The signal is generated by an optical DP-QPSK Transmitter, and is then propagated through the fiber loop where dispersion and polarization effects occur. It then passes through the Coherent Receiver and into the DSP for distortion compensation. The fiber dispersion is compensated using a simple transversal digital filter, and the adaptive polarization de-multiplexing is realized by applying the constant-modulus algorithm (CMA). A modified Viterbi-and-Viterbi phase estimation algorithm (working jointly on both polarizations) is then used to compensate for phase and frequency mismatch between the transmitter and local oscillator (LO) [16]. After the digital signal processing is complete, the signal is sent to the detector and decoder, and then to the BER Test Set for direct-error-counting.

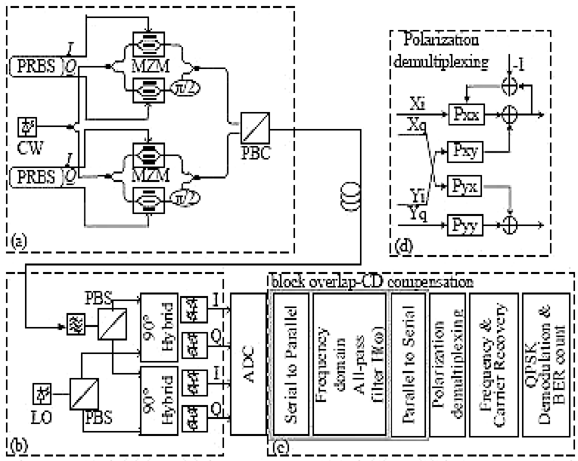

Fig 4. Coherent DP-QPSK system configuration: (a) DP-QPSK transmitter, (b) Coherent receiver optical front end, (c) Off-line DSP algorithms blocks, (d) Polarization de-multiplexing buttery structure

IX. RESULTS AND DISCUSSIONS

Below some images of the optical spectrum of the 100 Gbps DP-QPSK signal after the transmitter, as well as the RF spectrum obtained after the Coherent DP-QPSK Receiver. Fig. 5 shows the analyzed optical spectrum after optical DP-QPSK transmitter of frequency 1550 nm and Fig. 6 is the analyzed RF signal spectrum of transmitter. Fig. 7 is the electrical constellation visualizer of polarization-X before the DSP algorithm. Fig. 8 unveils the receiver constellation diagram after DSP compensation, it gives effective spectrum efficiency in the view of high OSNR.

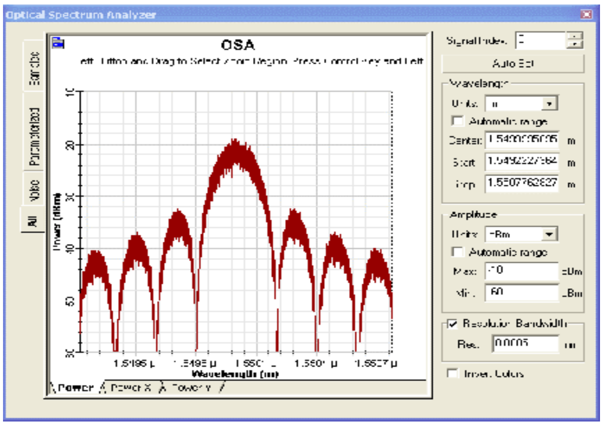

Fig 5. Optical Spectrum Analyzer after transmitter

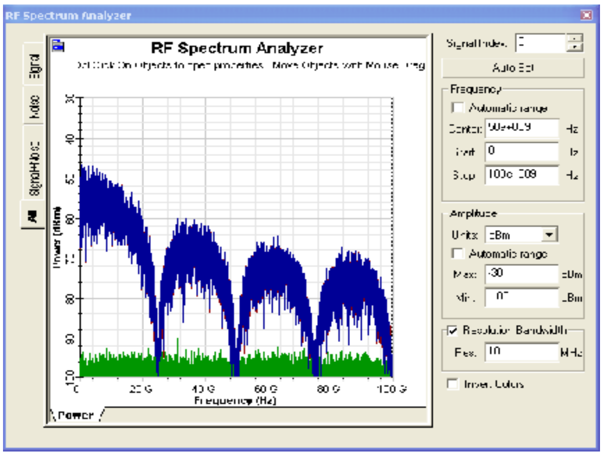

Fig 6. RF spectrum analyzer after transmitter

The electrical constellation diagrams (for polarization X) before and after the DSP are as follows:

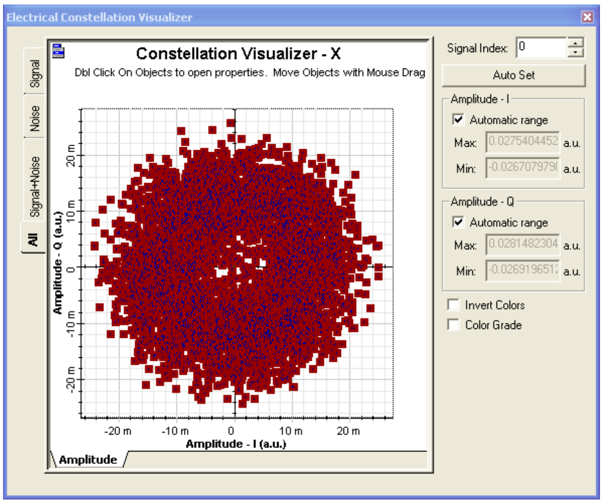

Fig 7. Electrical constellation visualize-X before DSP

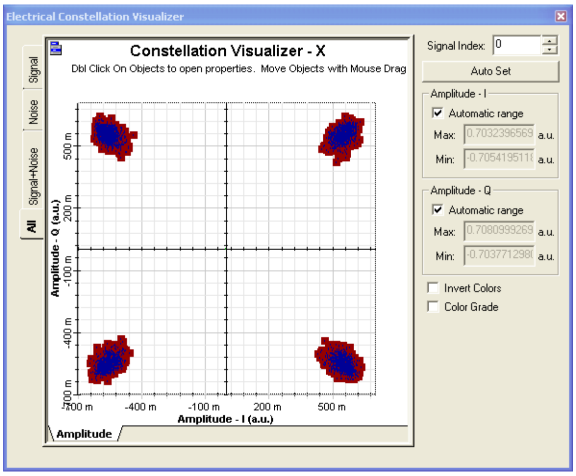

Fig 8. Electrical constellation visualize-X after DSP

The algorithms used for digital signal processing are implemented through a Matlab component. By setting the Matlab component to debug mode, the generated electrical constellation diagrams after each step (CD compensation, Polarization De-multiplexing, and Carrier Phase Estimation) are shown here:

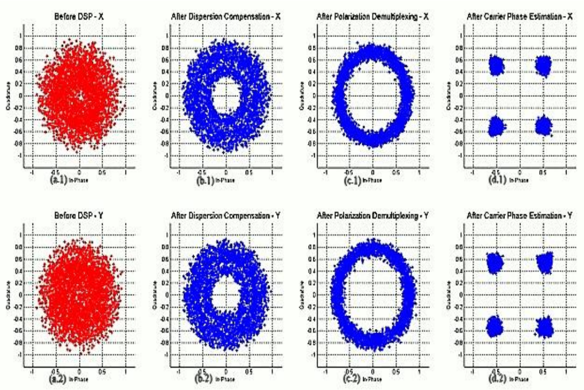

Fig 9. Matlab implementation of DSP algorithm. (a.1, a.2) before DSP of X & Y. (b.1, b.2) after dispersion compensation. (c.1, c.2) after polarization demultiplexing. (d.1, d.2) after carrier phase estimation

X. CONCLUSION

Coherent detection at 100 Gbps will become feasible in the future using DSP for linear impairments compensation. DSP facilitates polarization de-multiplexing, compensation of linear transmission impairments, as CD and PMD, and also gives higher OSNR tolerance. Improved OSNR tolerance leads to increasing the maximal propagation distance with less optical amplifiers, less noise and less costs of the system. On the other hand a more complex receiver is required as polarization tracking has to be performed but this is well paid by the improvement on system performance. The performance of DSP algorithm in nonlinear compensation deteriorates when inter channel nonlinearities become predominant.
Considering the future work, there are a lot of issues that can be addressed. First is to implement more complex and advanced adaptive algorithms for the PMD and residual CD compensation (especially step size updating algorithms). Investigation over nonlinear effects compensation would also be interesting. Advanced techniques based on Volterra compensator are interesting because can avoid this problem.

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