A Survey on Digital Nonlinearity Compensation Techniques for Optical Fiber Communication Systems

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***Abstract*—The ever increasing demand of information requires highly spectral efficient coherent optical systems with advanced modulation formats which allows the detection of in-phase and quadrature-phase components of both polarizations and doubles the available capacity and spectral efficiency but the optical signal is severely degraded by nonlinear impairments. Among numerous distortions, inter-channel interference and intra-channel interference in multi-user wavelength-division multiplexing is identified as the seemingly intractable factor limiting the achievable rate at high launch power. Since the deployment of optical communication systems, different fiber technologies have been used to deal with optical fiber impairments. In this paper, a survey on the fiber non-linearity compensation techniques has been summarized. We focus on the well-known Digital Back Propagation based Memory Polynomial techniques, their performances and implementation complexity.**

***Index Terms*—Digital back propagation, memory polynomial, fiber non linearity compensation, digital signal processing**

I. Introduction

To satisfy the exponential growth in global Internet traffic,the development of transmission links that not only have high capacity but are also flexible, re-configurable, and adaptive is imperative.This has resulted in an unprecedented demand in the speed and volume of data transfers. As forecasted by Cisco this demand will definitely continue to grow and global data traffic will increase nearly 3-fold during five years time [1]. To meet the ever-increasing traffic demand, superchannel concept has been introduced, which splits the Wave Division Multiplex (WDM) channel into multiple subcarriers.
Orthogonal Frequency Division Multiplexing (OFDM) [2] and
Nyquist WDM [3] type super-channels are investigated. [4] However, such communication systems are highly vulnerable to fiber nonlinear effects, whose compensation is required to reach the desired data rate. High-order modulation formats require high Optical Signal-Noise Ratio (OSNR) and consequently, increase of the peak-to-average power ratio, which results in an increase of the nonlinear distortion. In Space Division Multiplexing (SDM), the data rate can be increased by introducing multi-mode/core fibers make the development of the optical amplifier more challenging [5]. Nonlinear Frequency Division Multiplexing (NFDM) scheme removes deterministic inter- and intra-channel interactions [6].

The paper is organized as follows. In Section II, a brief overview of nonlinear impairments in the optical link is presented. Section III, is focused on the Non Linear Compensation (NLC) techniques in digital domain, and described the well-known NLC techniques to provide an overview of other NLC approaches, such as Digital Back Propagation (DBP),Volterra Non Linear Equalizer(VLNE), and perturbation-based NLC and other extensions related to these methods. A detailed theoretical description of these techniques, along with their implementation, advantages and drawbacks is presented. Section IV is dedicated to the comparison of the main NLC techniques, in terms of performance and complexity. Finally, the Section V is concluded the paper by giving the lessons to be learned related to the NLC, techniques in digital domain.

II. Overview of Nonlinear Impairments in Optical Link

Nonlinear effects in optical fibers mainly occur due to the change in the refractive index of the medium with optical intensity the power dependence of the refractive index is responsible for the Kerr-effect. Depending upon the type of input signal, the Kerr-nonlinearity manifests itself in three different forms such as Self-Phase Modulation (SPM), CrossPhase Modulation (XPM) and Four-Wave Mixing (FWM). Nonlinear effects can also be caused by inelastic scattering that are usually not a major perfomance limiting factor [7]. Therefore,the work presented here mainly focuses the Kerrnon linearity.

The self-induced power-dependent phase shift experienced by an optical field during propagation in an optical fiber is known as SPM. In WDM, where multiple channels are transmitted simultaneously inside the fiber,the power of the neighboring channels causes nonlinear phase distortion for the channel of interest, referred as XPM. However,the severity of the distortion can be characterized by the number of channels and the spacing between adjacent channels [5]. In WDM transmission, the nonlinear interaction between light at different frequencies results in the generation of signals at new frequencies termed FWM and depends on the fiber dispersion as well as the channel spacing. In fact, FWM becomes significant when the channel spacing is narrow. XPolM results in the depolarization of the transmitted signal, which causes fading and cross-talk for dual-polarization systems, and can be modeled as an additive Gaussian process [8]. In super-channel approach, a small guard band is inserted between adjacent channels which will increase such nonlinear impairments dramatically.

The Nonlinear Schrodinger Equation (NLSE) that governs propagation in case of single-polarization is given by

$$\frac{\partial A(z,t)}{\partial z} + \frac{\alpha}{2}A(z,t) + j\frac{\beta_2}{2}\frac{\partial^2 A(z,t)}{\partial t^2} = j\gamma|A(z,t)|^2 A(z,t), \quad (1)$$

where A is the slowly varying amplitude of the pulse envelope and t is measured in a frame of reference moving with the pulse at a certain group velocity. Here, α is the fiber attenuation coefficient, β_2 is the second-order dispersion parameter, γ is the nonlinear coefficient of the fiber. Nonlinear Schrodinger equation in (1)is invertible and can be decomposed into linear and nonlinear components as $\frac{\partial A(z,t)}{\partial z} = (N + D)A(z,t)$ where $N = -j\gamma|A(z,t)|^2$ and. Hence, the receiver can be designed based on reverse NLSE in which the received signal can be reverse propagated through a filter with opposite signs of α, β_2 and γ for the joint mitigation of linear and nonlinear dispersion [9].

$$D = -\frac{\alpha}{2} - j\frac{\beta_2}{2}\frac{\partial^2}{\partial t^2}$$

Fiber nonlinear effects can be modeled based on Volterra Series Transfer Function (VSTF). In fact, VSTF is a powerful tool for solving the equation given in (1). In general, propagation over fiber can be approximated to a 3rd order Volterra series [5],

$$Z(\omega) = H_1(\omega)A(\omega) + \int\int H_3(\omega_1, \omega_2, \omega - \omega_1 + \omega_2)A(\omega_1, \omega_2, \omega - \omega_1 + \omega_2) \times [A(\omega_1)A^*(\omega_2)]d\omega_1 d\omega_2 \quad (2)$$

where $(.)^*$ stands for the complex conjugate, and $H_1(\omega) = e^{-j\omega^2\beta_2 NL/2}$ and $H_3(\omega_1, \omega_2, \omega - \omega_1 + \omega_2) = \frac{-jC}{4\pi^2} H_1(\omega) \sum_{k=0}^{N-1} e^{-jk\beta_2 \Delta\Omega L}$ denote the first-order and third-order Volterra series kernels with $\Delta\Omega = (\omega_1 - \omega)(\omega_1 - \omega_2)$,

$$C = \frac{8}{9}\gamma\tilde{L} \text{ for } \tilde{L} = (1 - e^{-\alpha L})/\alpha.$$

III. Compensation Techniques

Nonlinear compensation techniques can be broadly classified as digital and optical compensations. This paper focused only on compensation techniques performed in digital domain such as pre-distortion [10], DBP and the DBP based memory polynomial methods.

A. Digital back propagation(DBP)

In the absence of noise, the transmitted signal can be found by solving the inverse of the NLSE in (1) by propagating the output signal with inverse parameters (β_2,γ,α) to invert the channel effects and obtain the pulse envelop $A(0,t)$. The fiber link is divided into several spans with small distance,and at each span, it is modeled as a concatenation of linear and nonlinear sections. Therefore, it normally requires multiple computation steps per each fiber span. In addition, a prior knowledge of system parameters to estimate distortion characteristics.

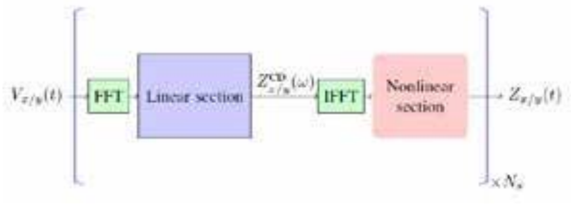

Fig. 1. Digital back propagation implementation principle

The output of the linear section, which compensates chromatic dispersion, is given by $Z^{CD}(\omega,z) = A(\omega, z)e^{-jh(\frac{\alpha}{2}+\frac{\beta_2}{2}\omega^2)}$ where h is the length of each span and an exponential term here, represents the inverse of the signal phase change due to the dispersion and fiber loss. After that the nonlinear compensation is applied in time domain to deal with the Kerr induced nonlinear effects. The implementation of the DBP technique at the receiver side is shown in Fig. 1, where N_s is the number of spans. In spite of the high computational complexity, DBP has been proposed as a universal technique for jointly compensating for the linear and nonlinear impairments and is often used to benchmark against other detectors [11]. It should be noted that the performance of DBP is limited by the Amplified Spontaneous Emission (ASE) noise which is non-deterministic and cannot be back propagated [9]. Many flavors of DBP were suggested for reducing the complexity including weighted DBP [12], perturbation DBP [13], folded DBP [14] and filtered DBP [10]. All these techniques aim to reduce the step-size requirements by improving the performance. A comprehensive survey of such approaches can be found in [11]. Maximum a posteriori principle based algorithm was proposed in [15] using the framework of factor graphs. In contrast to DBP, it accounts for the noise from the optical amplifiers and is proposed to deal with the non-deterministic effects.

Not even single-channel, multi-channel DBP techniques were proposed in [5] to combat nonlinear effects such as FWM, XPM and XPolM. Total-field DBP (TF-DBP) proposed in [16] experiences implementation constraints due to unavailability of high-speed analog/digital converters. Furthermore, it requires a smaller step size to give better performance than the single-channel DBP. A coupled-equation DBP approach has been proposed [16] to reduce the complexity involved in TFDBP while compensating XPM coupled nonlinear interference caused by adjacent subcarriers. This approach can be applied among independent receivers unlike TF-DBP,which requires the preservation of the relative phase between all subcarriers. Advanced-DBP has been also proposed for nonlinearity mitigation in super-channel systems [17].

B. Volterra series based nonlinear equalizer (VNLE)

Fiber nonlinear effects can be modeled based on the Volterra series transfer function (VSFT) explained in (2). VSTF is a powerful tool for solving the NLSE in (1), and Volterra kernels can be updated using either least mean square or the recursive least square methods. After modeling the optical channel,the p-th order nonlinear equalizer can be developed to derive the inverse VSTF kernels as a function of VSTF kernels $H_i(\omega), i = 1,3$ [5] like in DBP. VNLE can be processed in both frequency and time domains [5].

VNLE performances in super-channel transmission is decreased because of nonlinear interference caused by the adjacent subcarriers. To overcome this problem, a novel technique called Inter-subcarrier Nonlinear Interference Canceler (INIC) was proposed [5]. This is kind of a decision feedback equalizer which makes use of the prior knowledge of the detected adjacent subcarriers interference. Fifth-order VNLE has proposed in [5] performs well compared to the third-order approximation. In [18], authors proposed a nonlinear compensation technique by cascading a nonlinear memory polynomial based equalizers and DBP-SSFM where only diagonal terms of the Volterra kernels are considered. By imposing a frequencyflat approximation to the higher-order terms that are usually neglected in the commonly used VSTF approach, it is possible to reduce the overall expression order to the typical third-order plus an introduced complex correction factor [19]. Moreover, since the VSTF method is based on matrix multiplications, it allows for a parallel implementation, which reduces the computational complexity in the DBP/VNLE problems as well. The Wiener-Hammerstein model-based equalizer has been proposed in [20] very similar the basic VNLE. This model has a lower complexity than the Volterra series based equalization [5].

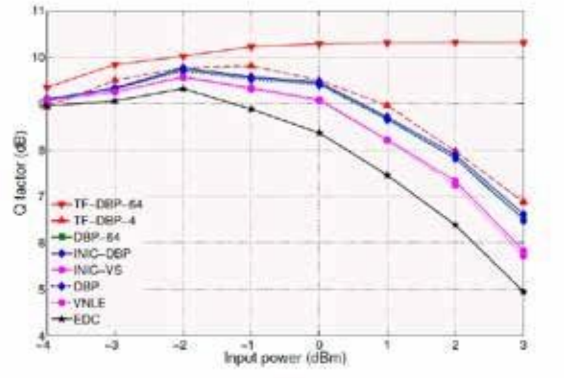

Fig. 2. Q-factor vs. the input power $\Delta = 1.1$.

C. Perturbation based nonlinearity compensation(PB-NLC)

Perturbation based approach have been extensively studied as a nonlinear compensator applied either at the transmitter side,as a pre-distortion, or at the receiver side. The main idea of PB-NLC technique is the use of the nonlinear distortion as a perturbation correction of the unperturbed solution. Based on the first-order perturbation, the received field can be written as $Z = Z_0 + \gamma\delta Z$ where Z_0 corresponds to the solution to linear propagation and δZ represents the firstorder perturbation which ultimately coincides with the third-

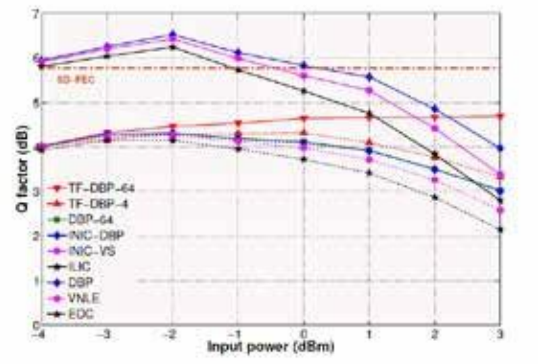

Fig. 3. Q-factor vs. the input power $\Delta = 0.95$.

order Voterra series approximation [5]. Whether it can be implemented as a single stage for the entire link, identification of a correct set of perturbation coefficients becomes a very difficult task specially in dynamically re-configurable meshed optical network architectures.

IV. Performance analysis

The performance of the NLC techniques was shown in terms of the Q-factor and subcarrier spacing factor. The Q-factor is again interpreted as $Q = 20\log\left(\sqrt{2}\text{erfc}^{-1}(2\text{BER})\right)$ where the Bit Error Rate (BER) is the ultimate indicator for measuring transmission quality. The subcarrier spacing factor is defined as the ratio between the sub carrier spacing Δf and the symbol rate R; $\Delta = \Delta f/R$.

In this section, performance analysis is carried out for the DBP(N_s = 1,64), TF-DBP (N_s = 4,64), VNLE, INIC-DBP and INIC-VS with N_s = 1. Here, linear Electronics Dispersion Compensation (EDC) is considered as a baseline reference. All results demonstrated here are only concern the performance around the central subcarriers, as they are the once more prone to interference. A dual-polarized 16-QAM modulated NyquistWDM super-channel with 4 subcarriers is considered. The input power corresponds to the launched power per subcarrier, and the transmission distance is considered as 1000 km [5].

Fig. 2 shows Q-factor performance due to nonlinear interference where there is no cross-talk involved (Δ = 1.1). TF-DBP-64 (refers N_s = 64) outperforms and significantly increasing with the input power. On the other hand, the performances of INIC techniques show almost align with the performance of DBP and VNLE as INIC techniques take a part of the nonlinear interference into account because of the causality issue [5]. In Fig. 3,where Δ = 0.95, decision feedback type equalizers exhibit the best performance in comparison to other techniques due to the cancellation of the linear cross-talk. Fig. 4 shows the complexity of the compensation techniques discussed above as a function of the number of spans N_s. The FFT size used for complexity evaluation is 1024 [5]. INIC-based single-step compensation techniques have relatively lower complexity in comparison

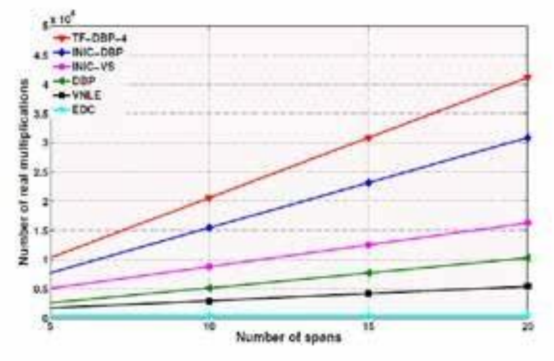

Fig. 4. SNR vs. launch power

with multi-step models per span.

V. Conclusion

We provided a comprehensive study of digital non linearity compensation techniques along with the performance and the computational complexity. Pre-distortion, DSP and Volterra based interference cancellation techniques were investigated. DBP-INIC shows significantly improved performance in and super-Nyquist WDM systems. This approach outperformed the classical nonlinear mitigation techniques. An improvement in terms of Q factor and sub carrier spacing was also observed. Moreover, it is noticed that the INIC-VS has significantly improved the performance in multi-band environment.

It is shown that VNLE performance in super-channels decreases due to the nonlinear adjacent channel interference while TF-DBP requires smaller step size to perform well in that domain. Further, in a long transmission distance, transceiver SNR with ASE beating shows a significant drop. Although the distance is increased at any degree the line converges in to a certain level. It should be also noted that, when increasing the transmission distance transceiver SNR with ASE beating falls to a low degree While transceiver SNR without ASE beating shows a gradual growth. The integration of memory polynomial is promising approach to reduce the complexity associated with DBP-based techniques.

As a future work, one can remark that the INIC implementation can rely on DBP instead of Volterra series. INICDBP method requires further numerical simulations and/or experimental validations can be also used for combating the intra-band/sub carrier nonlinear effects.The major constraint when considering intra band/sub carrier nonlinear effects is the causality issue. ASE shows up as a strong limiting factor for the performance when the transmission distance is relatively large. A study on interactions of transceiver noise with ASE noise might be a suitable direction to move on.