RESEARCH ARTICLE OPEN ACCESS

Analyais Of Coherent Optical OFDM System using Adaptive Volterra Equalizer

Ashwini S.Dharashive [1] , S.S.Killarikar [2]
Department of E&TC, M.S.Bidve Engineering College ,Latur

ABSTRACT
This paper addresses OFDM (orthogonal frequency division multiplexing) transmission over optical links with high spectral efficiency, i.e. by using high-order QAM-modulation schemes as a mapping method prior to the OFDM multicarrier representation. Here we address especially coherent optical OFDM modem in long distance which is affected by nonlinear distortion caused by fiber nonlinearity. Fiber nonlinearity is a major performance-limiting factor in advanced optical communication systems. We proposed a nonlinear electrical equalization scheme based on the Volterra model. To Compare with other popular linear compensation technique such as the LMS (least Mean Square), simulation results are presented to demonstrate the capability of a Volterra model based electrical equalizer used in a coherent optical orthogonal frequency division multiplexing system. It is shown that the Volterra model based equalizer can significantly reduce nonlinear distortion.

Keywords— Equalizers, optical fiber communication, orthogonal frequency division multiplexing (OFDM), Volterra model.

Date of Submission: 04-09-2022 Date of Acceptance: 19-09-2022

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) has been used in many telecommunication applications because of its high spectral efficiency and simple hardware implementation. OFDM has also been considered for optical systems as a candidate for future long range high data rate communication systems [1,2]. As described in [1], OFDM suffer of very strong fiber nonlinearities such as interchannel Four wave mixing (FWM) and cross-phase modulation (XPM) and intrachannel self-phase Modulation (SPM) [1] – [2]. For that reason, prior knowledge about transmission aspects such as intrachannel and interchannel nonlinearities and their dependence on link length and signals constellation Order is mandatory for the system to convey information in a reliable way. This can be addressed by recurring to mathematical models capable of analyzing and simulating accurately the system' s performance and different contributions of the most relevant physical impairments. On that regard, by using a Volterra series approach, one is able to estimate the signal to noise ratio (SNR) of the received constellation with respect to different nonlinearities effect. Volterra series have gained a lot of attention from the optical communication community over the past years on research topics such as: modeling the optical fiber [3];post processing nonlinear equalizer on coherent systems [4]– [5]; analysis of fiber nonlinearities [6]– [7]. In this section, we present the impact of the most relevant fiber nonlinearties such as SPM, XPM and FWM on Coherent Optical OFDM system using Volterra series.

This chapter addresses transmission aspects on Coherent Optical OFDM modem, and it covers the impact on the system' s performance of the most relevant fiber Nonlinearities such as self-phase modulation (SPM) , cross-phase modulation (XPM) and four-wave mixing (FWM) , and their interplay between Transmission distance and modulation format Using a Volterra series Method allows estimating the error vector magnitude (EVM) of the received constellation related to different fiber nonlinearities. This EVM reduction confirms that increasing the transmission distance and the order of the constellation, the system' s performance becomes limited by both interchannel FWM and XPM. For a time and frequency-varying channel such as a SMF link, equalization is considered as a very effective solution, many equalization techniques were adopted in the wireless and optical communication systems such as AE, and Volterra. Consequently the scope of this chapter is to study the effect of AE using Wiener-Hammerstein, Volterra, sparse volterra, MLSE equalizers on bit error rate versus transmission distance performance.

In this paper, the nonlinear effect of a high order modulation, 10 Gbit/s CO-OFDM system is investigated. Electrical equalizers based on the linear model, conventional Volterra model, and LMS model are designed and tested in simulations. The rest of this paper is organized as follows: In second section, simulation set up of the CO-OFDM system which is used in our study is described, third section the simulation results and discussions are presented, and the fifth section includes conclusion of the work.

II. COFDM SYSTEM DESCRIPTION

Figure 1 shows the conceptual diagram of a generic CO-OFDM system, including five basic functional blocks: RF OFDM transmitter, RF-to-optical (RTO) up-converter, optical link, optical-to-RF (OTR) down-converter, and RF OFDM receiver [15, 16, 17, and 18]. In the RF OFDM transmitter, the input digital data are first converted from serial to parallel into a " block" of bits consisting of Nsc information symbol, each of which may comprise multiple bits for m-ary coding. This information symbol is mapped into a two-dimensional complex signal Cki, for instance, using Gray coding, where Cki stands for the mapped complex information symbol. The subscripts of Cki correspond to the sequence of the subcarriers and OFDM blocks. The time domain OFDM signal is obtained through inverse discrete Fourier transform (IDFT) of Cki , and a guard interval is inserted to avoid channel dispersion [9,10] The resultant baseband time domain signal can be described as :

$$s_B(t) = \sum_{i=-\infty}^{+\infty} \sum_{k=-\frac{N_{sc}}{2}+1}^{k=N_{sc}/2} c_{ki}\Pi(t - Ts)e^{j2\pi f_k(t-iT_s)} \qquad (1)$$

Where:

$$f_k = \frac{k-1}{t_s} \qquad (2)$$

$$\Pi(t) = \begin{cases} 1, (-\Delta G < t \le t_s \\ 0, t \le -\Delta G, t > t_s \end{cases} \qquad (3)$$

Where Cki is the i[th] information symbol at the kth subcarrier; f_k is the frequency of the k[th] subcarrier; is the number of OFDM subcarriers Ts, ΔG, and ts are the OFDM symbol period, guard interval length, and observation period, respectively; and $\Pi(t)$ is the rectangular pulse waveform of the OFDM symbol. The extension of the waveform in the time frame of [-ΔG, 0] in (1) represents the insertion of the cyclic prefix, or guard interval. The digital signal is then converted to an analog form through a DAC and filtered with a low-pass filter to remove the alias signal. The baseband OFDM signal can be further converted to an RF pass band through an RF IQ. The subsequent RTO up-converter transforms the base band signal to the optical domain using an optical IQ modulator comprising a pair of Mach– Zehnder modulators (MZMs) with a 90 degree phase offset. The baseband OFDM signal is directly up-converted to the optical domain which is given in [17] by:

$$E(t) = e^{j((w_{LD1}t+\varphi_{LD1})}.s_B(t) \qquad (4)$$

Where ω_{LD1} and φ_{LD1} are the angular frequency and phase of the laser respectively. The up-converted signal E (t) traverses the optical medium with an impulse response of E (t) , and the received optical signal becomes:

$$E'(t) = e^{j((w_{LD1}t+\varphi_{LD1})}.s_B(t) \otimes h(t) \qquad (5)$$

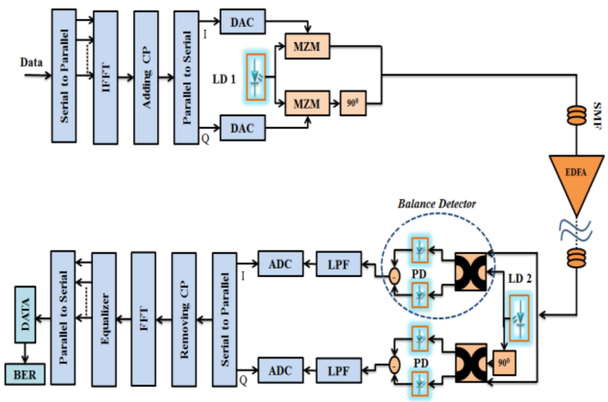

Fig. 1 Conceptual diagram for a generic CO-OFDM system with a direct up/down conversion architecture

Where, ⊗ stands for convolution. The optical OFDM signal is then fed into the OTR down converter, where the optical OFDM signal is converted to an RF OFDM signal. The directly down-converted signal can be expressed as:

$$r_0(t) = s_B(t) \otimes h(t) \qquad (6)$$

$$\omega_{off} = \omega_{LD1} - \omega_{LD2} \qquad (7)$$

$$\Delta\varphi = \varphi_{LD1} - \varphi_{LD2} \qquad (8)$$

$$c'_{ki} = e^{j\Phi_i} e^{j\Phi_D(f_k)} T_k c_{ki} + n_i \qquad (9)$$

$$\Phi_D(f_k) = \pi.c.D_t.\frac{f_j^2}{f_0^2} \qquad (10)$$

$$c'_{ki} = E'(t) \tag{11}$$

Where ω_{off} and $\Delta\varphi$ are the angular frequency offset and phase offset between the transmitted and receive lasers respectively. $\Phi_D(f_k)$ is the phase dispersion due to the fiber chromatic dispersion. Φ_i is the OFDM common phase error (CPE) due to the phase noises from lasers and RF local oscillators. The optical transmission link is set up using a single channel CO-OFDM system with & without equalizer compensation by using matlab simulation for the transmitter and receiver blocks. Our simulation set up takes key optical communication system/component' s parameters into account including fiber nonlinearity, noise, dispersion, and PMD etc.

The data transmission bit rate is 10 Gbps. On the transmitter side, a bit stream is generated using a pseudo random binary sequence generator, and the data is mapped by a 4-QAM encoder. The information stream is further parsed into 64 low speed parallel data subcarriers and processed by the IFFT processor. Cyclic prefix is added to ensure a correct data recovery.

The Mach– Zehnder modulator is used to convert electrical signals to optical signals. The laser line width is set at 0.15MHz, with adjustable launch power. The frequency of the carrier wave is set at 193.1THz. The optical channel consists of standard single mode fiber (SSMF) with attenuation = 0.2dB/km, dispersion = 17 ps/nm/km and nonlinearity coefficient=2.09 /w/km. Span loss is balanced by a 4 dB noise figure optical amplifier in each loop. Amplified spontaneous emission (ASE) noise is reduced by an optical filter at the receiver. The local oscillator (LO) laser is assumed to be perfectly aligned with power set at -2dBm and linewidth equals to 0.15 MHz. Photo-detector noise, such as thermal, shot noise, dark current and ASE noise are included in the simulation. The converted OFDM RF signal is demodulated using FFT processor and the guarding interval is removed. The obtained signals are fed into a 4-QAM decoder. Transmission bits are collected and bit error ratio (BER) is calculated for the system at the end of the receiver.

As stated previously, IFFT parallel input data is typically data that has been modulated using QAM. One QAM symbol is described by one complex number. This QAM data is in turn modulated onto OFDM subcarriers by the IFFT. At the receiver, the phase shifted versions of the original transmitted subcarriers are processed using the FFT and the output is the transmitted QAM data with channel effects. The relative change in phase which is caused by dispersion manifests itself as a shift in phase of each QAM symbol. The channel frequency response causes different subcarriers to have different channel gains and this affects the magnitudes of the QAM symbols. Therefore, in order to retrieve the QAM data correctly, it is necessary to estimate these channel effects and account for them by equalizing the data accordingly.

The solution to this particular problem is to use a Training Sequence (TS). This is a known sequence of complex numbers that is used as the input to the N dimensional IFFT and therefore results in one OFDM symbol. It is common to transmit this sequence more than once throughout an entire OFDM signal. As the training sequence constitutes one entire OFDM symbol, and therefore contains every subcarrier, information about the channel effect on every subcarrier can be obtained by comparing the transmitted and received training sequences. This is known as channel estimation. This can be described simply in mathematical terms. For a given channel response H and known input X the output is [21]:

$$Y = H.X \tag{12}$$

Since in this case the input and the output both are known, we can estimate the channel as:

$$H_{est} = Y / X \tag{13}$$

H_{est} describes the effect of the channel on every OFDM subcarrier. To reverse the channel effect on all subsequent data , we simply invert the channel estimation H_{est} and apply the resulting equalizer to all subsequent data. The practical implementation of this in DSP is also straightforward. Since both the transmitted and received training sequences consist simply of a vector of N complex numbers, so too does the channel estimation, H_{est}. It follows that this equalizer vector can be seen as a bank of N equalizers which is used to reverse the channel effects of each subsequent corresponding N QAM symbols, following receiver demodulation by the FFT.

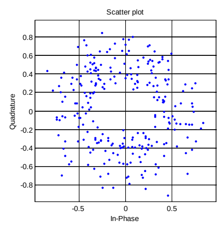

Fig. 2 Constellation without equalization

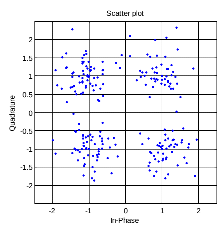

Fig. 3 Constellation after equalization

III. SIMULATION RESULTS

As its mentioned in [Reis][pend], using Volterra theory we are able to estimate the error vector magnitude of the received symbols associated with the most relevant fiber nonlinear effects: self phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM). That being the case, we firstly transmitted the 10 Gb/s through SSMF employing third order Volterra series transfer function (VSTF) method As in [4], the most nonlinearity effect for long-haul coherent optical OFDM is FWM, we have studied in this section after the determination of the mathematical model of each effect as developed in [reis]-[giacoumidis], all nonlinearity effect with the VSTF model. The simulated received signal constellation diagram after 2000 km fiber transmission, with -2 dBm laser launch power is shown in Figure 4 and Figure 5 Due to fiber nonlinearities, the constellation .diagram has become scattered and has phase and amplitude distortions. As shown in the constellation diagram, there is no doubt that nonlinear equalizers outperform compensation on nonlinearities and noise.

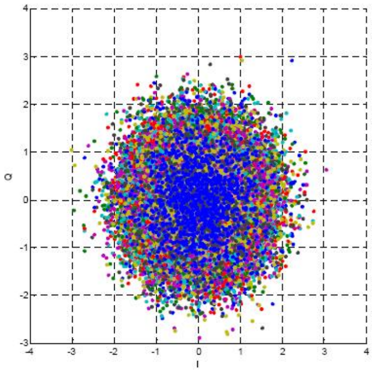

Figure 4 *Output signal constellations of the 4-QAM CO-OFDM system without equalizer*

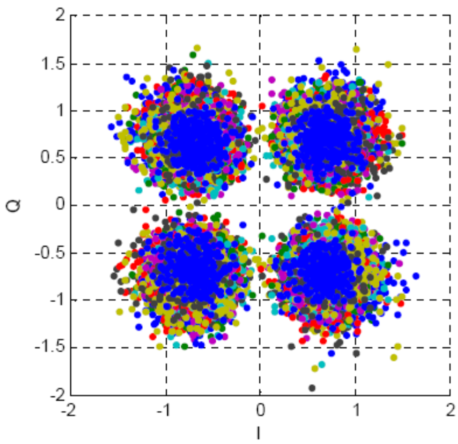

Figure 5 *Output signal constellations of the 4-QAM CO-OFDM system with Volterra equalizer*

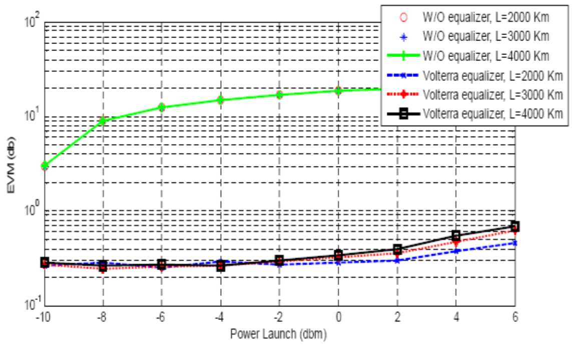

Figure 6 *EVM VSTF with and without Volterra Equalizer*

Figure 6 shows the EVM of Coherent Optical OFDM with RLS and Volterra equalizers, equalization at different power launch from -10 dbm to 6 dbm. It is not surprising that by increasing power launch the system performance deteriorated. The outperformance of nonlinear equalizers becomes more evident by comparison of the systems with and without equalization, also these simulations confirm that increasing the transmission distance, the system performance becomes limited by both interchannel FWM and XPM.The simulated received signal constellation diagram after 1400 km fiber transmission, with 0 dBm laser launch power is shown in Fig. 7, Fig. 8 and Fig. 9. Due to SPM, ASE noise and photodetector noise, the constellation diagram has become scattered and has phase and amplitude distortions. The linear kernels account for the attenuation and the dispersion effect of fiber. The third-order kernels can account for the interaction between ASE noise and signal and nonlinear distortions [12]. Since linear equalizer has no nonlinear terms, its capability of removing the phase noise introduced by fiber nonlinearity is restricted. As shown in the constellation diagram, there is no doubt that nonlinear equalizers outperform the linear equalizer.

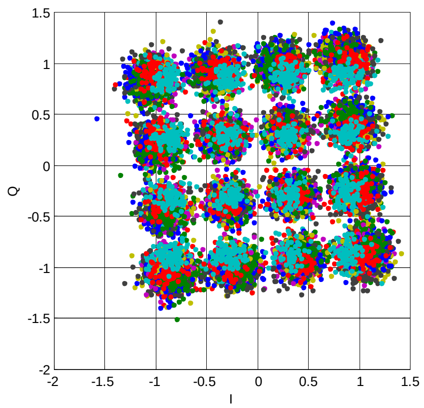

Figure 7 Output signal constellations of the 16-QAM CO-OFDM without equalizer,

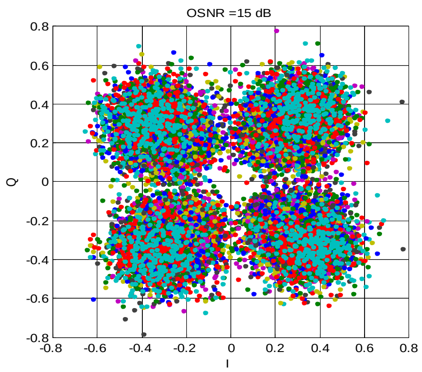

Figure 8 Output signal constellations of the 4-QAM CO-OFDM system with linear equalizer

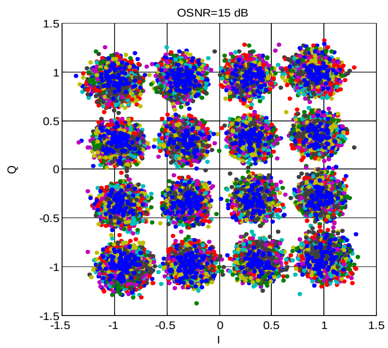

Figure 9 Output signal constellations of the 16-QAM CO-OFDM system with Volterra equalizer

For comparison purpose, the adaptive linear equalizer is also included in the simulation to evaluate the performance of nonlinear equalizers. The received signal constellation diagram after 800 km fiber transmission, with 0 dbm launch power is shown in Fig. 7, 8,9. Due to SPM, ASE noise and photodetector noise, the constellation diagram has become scattered and has phase and amplitude distortions. The linear kernels account for the attenuation and the dispersion effect of fiber, while the third order kernels can account for the interaction between ASE noise and signal and nonlinear distortion [12]. Since linear equalizer has no nonlinear terms, its capability of removing the phase noise introduced by fiber nonlinearity is restricted. As shown in the constellation diagram, there is no doubt that nonlinear equalizers outperform the linear equalizer.

IV. CONCLUSION

This paper presents the investigation on system nonlinearity of single channel 10 Gbit/s with high order modulation CO-OFDM systems and its compensation. The Volterra model based electrical equalizer has been shown capable of compensating intra-channel nonlinearity of the CO-OFDM system.

REFERENCES

[1]. Shieh.W and Authadage C. coherent optical orthogonal frequency division multiplexing; electronic letters.42(10),587– 589 (2020).
[2]. Shieh.W,Yang.Q, and MA.Y.107 Gb/s coherent optical ofdm transmission over 1000km SSMF fiber using orthogonal band multiplexing, optics express,16(9),6378– 6386 (2018).
[3]. W. Shieh, H. Bao, and Y. Tang, " Coherent optical OFDM: Theory and design," Opt. Exp., vol. 16, pp. 842– 859, Jan. 2008.
[4]. E. Ip, A. P. T. Lau, D. J. F. Barros, and J. M. Kahn, " Coherent detection
[5]. in optical fiber systems," Opt. Exp., vol. 16, pp. 753– 791, Jan. 2008.
[6]. W. Shieh and I. Djordjevic, OFDM for Optical Communications.New York: Elsevier, 2010, ch. 7.
[7]. I. Kaminow and T. Y. Li, Optical Fiber Telecommunications IVB.New York: Academic, 2002.
[8]. R. van Nee, " OFDM codes for peak-to-average power reduction and error correction," in Proc. IEEE Global Telecomm. Conf., 1996, pp.
[9]. 740– 744.
[10]. R. Weidenfeld, M. Nazarathy, R. Noe, and I. Shpantzer, " Volterra nonlinear compensation of 112 Gb/s ultra-long-haul coherent optical OFDM based on frequency-shaped decision feedback," in Proc. ECOC, 2009, pp. 1– 2.
[11]. M. Schetzen, The Volterra and Wiener Theories of Nonlinear Systems. New York: Wiley, 1980.
[12]. K. V. Peddanarappagari and M. Brandt-Pearce, " Volterra series transfer function of single-mode fibers," J. Lightw. Technol., vol. 15, pp. 2232– 2241, Dec. 1997.
[13]. J. D. Reis, L. N. Costa, and A. L. Teixeira, " Nonlinear effects prediction in ultra-dense WDM systems using Volterra series," in Proc, Opt. Fiber Commun. Conf. Collocated National Fiber Optic Engineers Conf., Mar. 21– 25, 2010, pp. 1– 3.
[14]. K. V. Peddanarappagari and M. Brandt-Pearce, " Volterra series approach for optimizing fiber-optic communications system designs," J.Lightw. Technol., vol. 16, no. 11, pp. 2046– 2055, Nov. 1998.
[15]. Y. Gao, F. Zhang, L. Dou, Zh. Y. Chen, and A. S. Xu, " Intra-channel nonlinearities mitigation in pseudo-linear coherent QPSK transmission system via nonlinear electrical equalizer," Opt. Commun Commun., vol. 282, pp.2421– 2425, 2009.

[16]. X. Zhu, S.Kumar, S. Raghavan, Y. Mauro, and S. Lobanov, " Nonlinear electronic dispersion compensation techniques for fiber-optic communication systems," in Proc. OFC/NFOEC, Feb. 2008, pp. 1– 3.
[17]. S. Jansen, I. Morita, H. Tanaka, " 10x121.9-Gb/s PDM-OFDM transmission with 2-b/s/Hz spectral efficiency over 1,000 km of SSMF," OFC, paper PDP2, 2008.