RESEARCH ARTICLE OPEN ACCESS

Performance Evaluation of High Speed Coherent Optical OFDM System Using Wiener-Hammerstein Equalizer

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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 Wiener-Hammerstein model. To Compare with other popular linear compensation technique such as the LMS (least Mean Square), Volterra equalizer simulation results are presented to demonstrate the capability of a Wiener-Hammerstein model based electrical equalizer used in a coherent optical orthogonal frequency division multiplexing system. It is shown that the Wiener-Hammerstein model based equalizer can significantly reduce nonlinear distortion.

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

Date of Submission: 29-06-2018 Date of acceptance: 14-07-2018

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, LMS model and Wiener – Hammerstein equalizer 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 Wiener – Hammerstein equalizer model are described, fourth section describe the simulation results and discussions are presented, and the fifth section includes conclusion of the work.

II. COFDM SYSTEM DESCRIPTION

Fig.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]. In the RF OFDM transmitter, the input digital data are first converted from serial to parallel into a "block" of bits consisting of N_{sc} 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 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 .

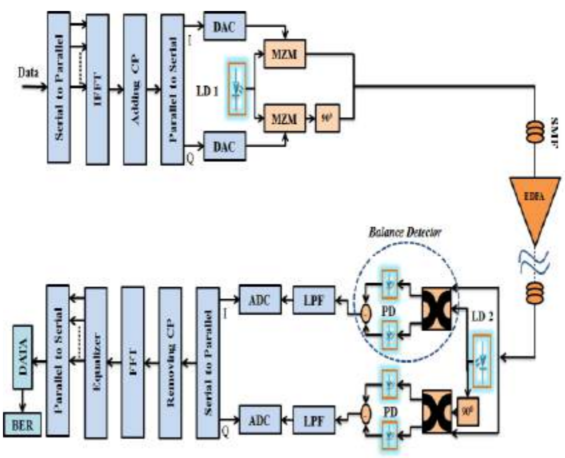

Fig. 1 Conceptual diagram for a generic CO-OFDM system with a direct up/down conversion architecture

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 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 parameters adopted throughout the simulation are given in Table 1.

Table 1 CO-OFDM transceiver parameters

Parameters	Values	Unit
No. of sub-carriers	128	—
Operating wavelength	1550	nm
Kerr nonlinearity coefficient	2.6×10^{-20}	m^2/W
Light source	ideal laser diode	—
Photodetector	PIN	—
Photodetector responsivity	0.9	—
Optical launch power	-6	dBm
Fiber span	100	km
Chromatic dispersion (CD)	17	ps/nm/km
Fiber loss	0.2	dB/km
EDFA gain	20	dB
EDFA noise figure	4	dB
CP length	25	%

III. WIENER HAMMERSTEIN MODEL

In this section, we detail one of alternative solution for nonlinear compensation: the Wiener-Hammerstein model. Wiener-Hammerstein model is one of the commonly used block-oriented nonlinear structures [13], which comprises a cascading association of a Wiener and Hammerstein systems. The Wiener system is composed by a linear filter attended by memoryless nonlinearity, while the Hammerstein system is composed by a memoryless nonlinearity followed by a linear filter. Consequently, the Wiener-Hammerstein model can be defined by memoryless nonlinearities sandwiched by two linear filters. Thememoryless function can be approximate as a polynomial of finite degree. This kind of nonlinear system has been used in the physiological system modeling [14], the power amplifiers modeling [15], the power amplifiers nonlinearity compensation , the acoustic echo cancellation the biological applications , and etc.

The employment of Wiener-Hammerstein model in LTE system is used to mitigate both multipath and nonlinear effects introduced respectively by multipath channel transmission and OFDM amplifier.

Fig. 2 depicts the Wiener-Hammerstein model, the first subsystem is the linear filter(FIR). The second subsystem is the nonlinear polynomial filter derived from memoryless nonlinearity sandwiched, and the third subsystem is another FIR filter [12].

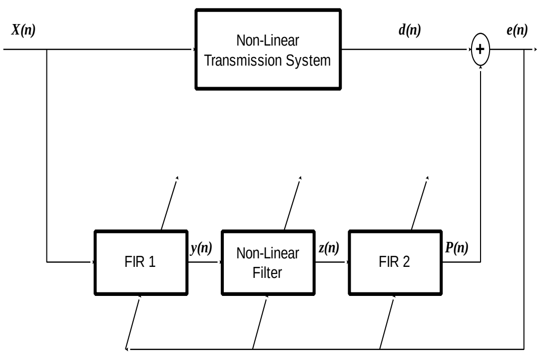

Fig.2 Wiener-Hammerstein system for channel modeling

After passing through the first FIR filter, the input-output relation in a discrete and time invariant form is displayed as following, where $M_1 - 1$ is the first FIR filter memory length.

$$y(n) = \sum_{i=0}^{M_1-1} u(i)x(n-i) \quad (1)$$

$$u(n) = [x(n), x(n-1), ..., x(n-j), ..., x(n-L+1)]^T \quad (2)$$

The multipath channel is considered as a pass band filter, so only the odd order terms in the “sandwiched” nonlinear subsystem can generate nonzero output and the even order terms are neglected. In this work, we choose the polynomial order of memoryless function equal to 3. The output signal after the center nonlinear filter is written as:

$$z(n) = v(0)y(n) + v(1)y^2(n)y^*(n) \quad (3)$$

The relationship between the output and the input signals of the second FIR filter is represented as follow :

$$P(n) = \sum_{i=0}^{M_1-1} w(i)z(n-i) \quad (4)$$

where $M_1 - 1$ is the second FIR memory length.

The difference between desired signal $d(n)$ and the filter output $P(n)$ is given by:

$$e(n) = d(n) - P(n)$$

IV. 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 3 and Figure 4. 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.

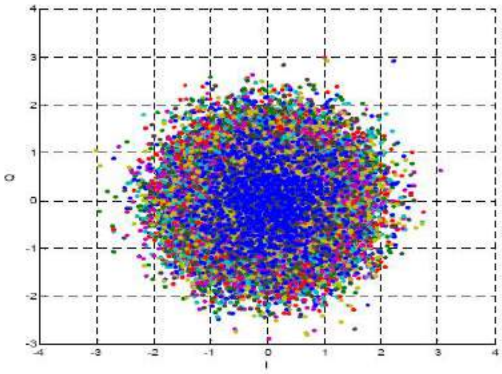

Fig.3 Output signal constellations of the 4-QAM CO-OFDM system without equalizer

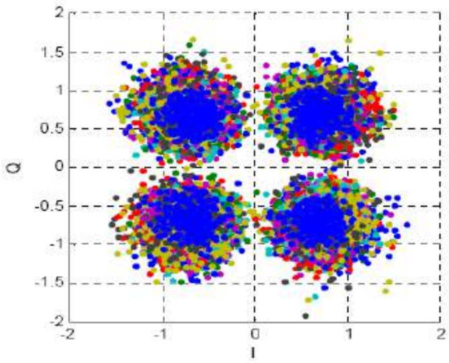

Fig. 4 Output signal constellations of the 4-QAM CO-OFDM system with Volterra equalizer

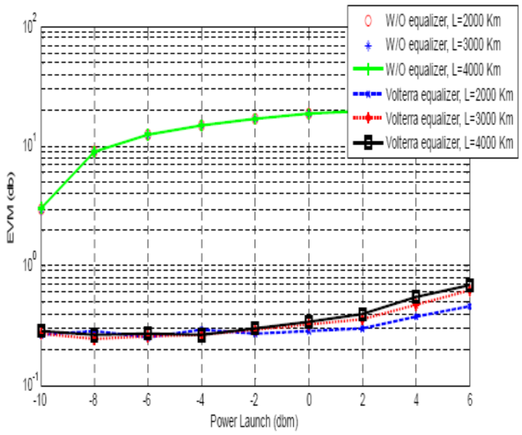

Fig 5 EVM VSTF with and without Volterra Equalizer

Fig. 5 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. 6, Fig.7 . Due to SPM, ASE noise and photodetector noise, the constellation diagram has become scattered and has phase and amplitude distortions.

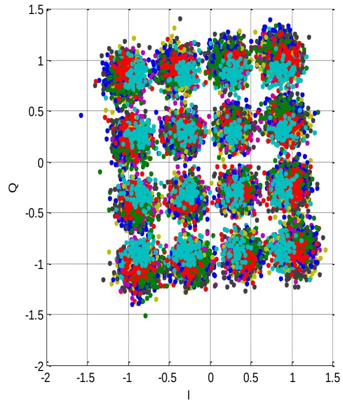

Fig.6 Output signal constellations of the 16-QAM CO-OFDM without equalizer,

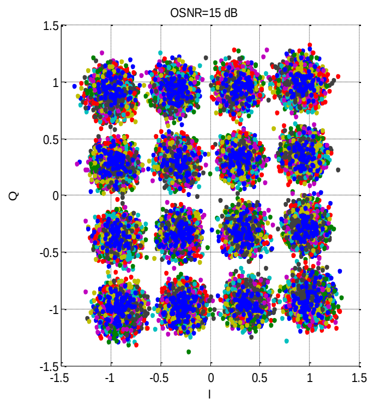

Fig.7 Output signal constellations of the 16-QAM CO-OFDM system with Volterra equalizer

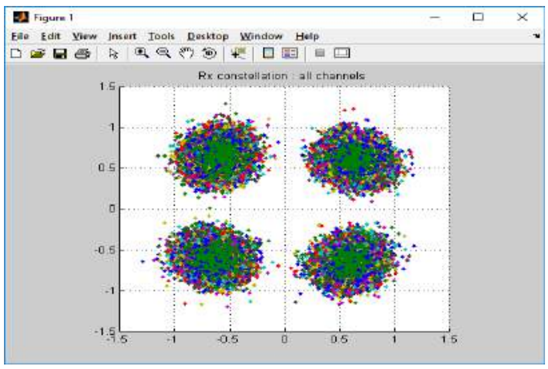

Fig.8 Output signal constellations of the 4-QAM CO-OFDM system with Wiener-Hammerstein equalizer for Nsc =128,order=4, power 0 dbm, L=1400 km

We have got below results
SNR = 19.8369
SNRdB = 12.9747
BER_actual =3.9102e-006
EVM_rms =0.2245

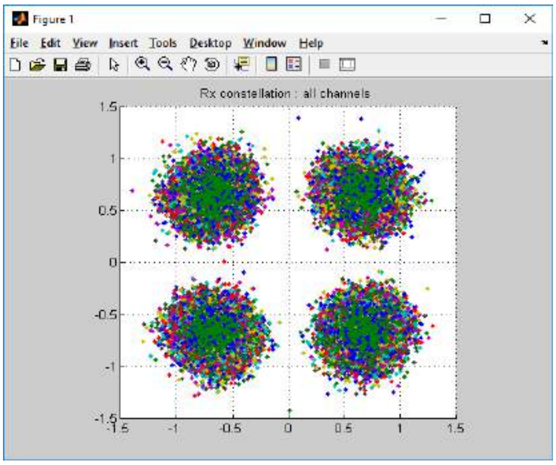

Fig. 9 Output signal constellations of the 4-QAM CO-OFDM system with Wiener-Hammerstein equalizer for Nsc =128,order=4, power 0 dbm, L=2000 km

We have got below results SNR =24.1081
SNRdB = 13.8216
BER_actual =3.9102e-006
EVM_rms = 0.2037

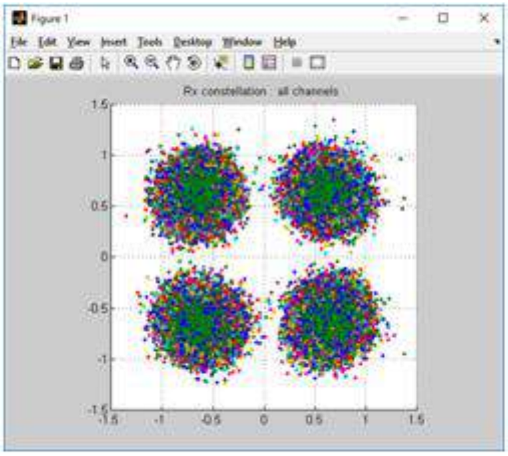

Fig.10 Output signal constellations of the 4-QAM CO-OFDM system with Wiener-Hammerstein equalizer for Nsc =128,order=4, power 0 dbm, L=3000 km

We have got below results
SNR =17.2928
SNRdB =12.3787
BER_actual =1.5641e-005
EVM_rms =0.2405

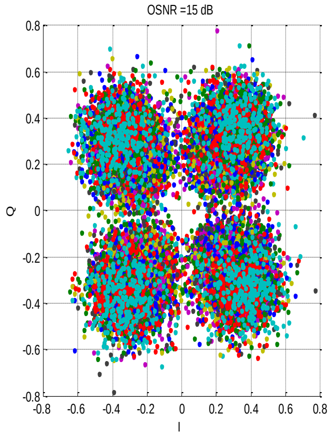

Fig.11 Output signal constellations of the 4-QAM CO-OFDM system with linear equalizer

Fig. 12 shows the BER of OFDM modem with linear, Volterra and Wiener-Hammerstein equalizers at different OSNR under 0 dBm laser launch power. It is not surprising that with the increase of OSNR, the system would have a better performance. The performance of nonlinear compensators becomes more evident with the increase of OSNR, since the signal becomes less distorted and the compensator coefficient determination becomes more accurate.

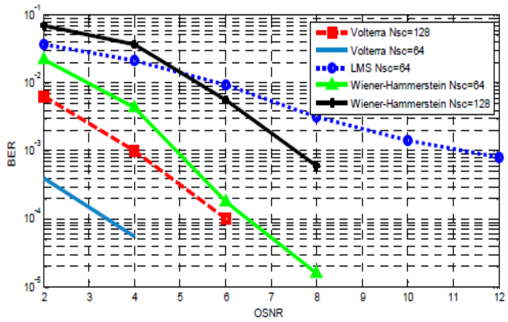

Fig. 12 Comparison between Volterra equalizer LMS equalizer and Wiener-Hammerstein equalizer 4-QAM,

V. 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 Wiener-Hammerstein model based electrical equalizer has been shown capable of compensating intra-channel nonlinearity of the CO-OFDM system.

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Vaishnavi P.Patil "Performance Evaluation of High Speed Coherent Optical OFDMSystem Using Wiener-Hammerstein Equalizer "International Journal of Engineering Research and Applications (IJERA) , vol. 8, no.7, 2018, pp.72-77