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40 & 100 Gb/s optical communications systems based on blind support vector machine with electrical equalizer

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This paper presents support vector machines (SVM) as a machine learning technique which is proposed as a method for performing nonlinear equalization in coherent optical CO-OFDM systems. The equalizer can offer a 7.75 dB improvement in optical signal-to-noise ratio (OSNR) compared to Volterra algorithm for 100 Gb/s CO-OFDM signals when considering only nonlinearities to achieve a Bit-Error-Ratio inferior to 10E-3. It is also revealed that SVM can double the transmission distance up to 1600 km over SMF compared to the case of Volterra and Hammerstein. The proposed algorithms are tested in simulation using a coherent 100 Gb/s 4-QAM optical communication system in a legacy optical network setting. We also present a blind-support vector machines (B-SVM) as a machine learning technique which is proposed as a method for performing nonlinear equalization in CO-OFDM systems. The B-SVM equalizer showed more efficiency in combating single-mode fiber (SMF) induced nonlinearities compared to the Volterra. The B-SVM equalizer can reduce the fiber nonlinearity penalty by 1 dB at 2 dBm of launched power improvement compared to Volterra algorithm for 40 Gb/s CO-OFDM signals. It is also shown that SVM-NLE outperforms both V-NLE and full-field DBP-NLE in terms of Q-Factor by ~6 and 1.5 dB, respectively.

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Keywords: Coherent optical OFDM, Blind SVM, Nonlinearities

1. Introduction

Coherent optical OFDM has many applications, such as, OFDM-PON, MIMO-OFDM and Direct-Detection Optical OFDM(DDO-OFDM) used in CATV network [1-2-3] and it is considered an enabling technology of the next generation optical communication system since it possesses the merits of both a coherent system and an OFDM system. However, One major concern people have about the CO-OFDM system is its vulnerability to fiber nonlinear effects [4-5-6], so it is need to mitigate this with equalization. Nonlinearity equalization has many field of concern [7], and has remained a challenging analytical problem for several reasons. Architectures for nonlinear equalizations often becomes unmanageably complex very rapidly, thus they requires novel techniques for limiting their degree of freedoms to make them useful. Moreover, the nonlinear systems requiring equalization is often non-invertible, resulting in a drastic loss of information. In addition, algorithms performing nonlinear equalization are often too computationally intensive to be run in real time implementation on FPGA [8,9].

In recent works based on Coherent Optical Orthogonal Frequency Division Multiplexing (CO-OFDM) signals transmission both Volterra filters [10,11] and neural networks [12-14] have been studied as techniques for nonlinearity compensation. In the case of Volterra filters, a multiplicative structure creates cross products of all filters states. These cross products are weighted linearly and the problem is to find the optimum weighting that minimizes some cost. The dimension of the model grows quickly and it becomes necessary some type of heuristic to limit that model [9].

We report also the research conducted by P. Guiomar et Al. in [12], in which a comprehensive study was carried out on the minimization of the Volterra Series Nonlinear Equalizer (VSNE) computational effort. Exploiting the symmetries shared by the 3rd-order VSNE kernels and the signal triplet matrices, author derive a loss less compressed VSNE formulation for polarization-multiplexed transmission, whose filter array structure benefits the trade-off between performance and complexity. In a similar work, the Channel Equalizer (CE) based on Independent Component Analysis (ICA) for CO-OFDM systems is studied without using Training Symbols (TSs) [13].

Moreover, the feasibility of zero-overhead PNC based on Decision-Directed Phase Equalization (DDPE) is reported for CO-OFDM transmission systems and numerically investigated its performance at 40 Gb/s after 2000 km transmission over uncompensated Single Mode Fiber (SMF) [14].

In this paper, we propose a novel SVM robust version for channel equalization that is specifically adapted to CO-OFDM data structure. The first contribution presented here is the use of complex regression in Support Vector Machine (SVM) formulation which is the best of our knowledge has not been investigated in Coherent Optical OFDM.

It is shown, that the Bit-Error Rate (BER) of a 100 Gb⁄s CO-OFDM system is less than the pre-forward-error-correction (pre-FEC) threshold of 10^{-3} after 3000 km of

SMF transmission. The fiber nonlinearity effect and the maximum achievable transmission distance of 100 Gb⁄s CO-OFDM can be enhanced for SVM equalization compared to Volterra and Wiener-Hammerstein equalization. In which, a maximum transmission distance of 800 km is achieved in [13,14].

Also, we propose a novel Blind-Support Vector Machine (B-SVM) version for channel equalization that is specifically adapted to CO-OFDM data structure. The second contribution presented here is the use of B-SVM formulation which is to the best of our knowledge has not been investigated in Coherent Optical OFDM. This is the first time that B-SVM used as an equalizer to mitigate nonlinearities on long-haul optical communications.

The rest of this paper is organized as follows: the SVM equalizer mathematical model description is performed in the first section. In the second section, the simulation results and discussions are presented. Finally, the conclusion is deduced in the third section.

2. SVM equalizer architecture

As pointed out in [3], equalization may be viewed as a classification problem. In such a scenario, the output of the receiver can be grouped as a vector and used as the input to a classification machine. Whose output should match as best as possible the desired output signal which is considered as some delayed version of the original signal entering the channel.

An optical fiber model can be made to fit the support vector model by grouping the output of the channel into vectors [3]:

$$x(n)=[x(n)x(n-1)....x(n-M+1)] \qquad (1)$$

and, for training purposes, taking the desired classification to be the input of the channel delayed by D samples, i.e.,

$$y_n = u(n-D) \qquad (2)$$

This model is illustrated in Fig.2 where the nonlinear channel has an Inter-symbol Interference (ISI) of length N.

To train the SVM let

$$X = [x(n-L+1)...x(n)] \qquad (3)$$

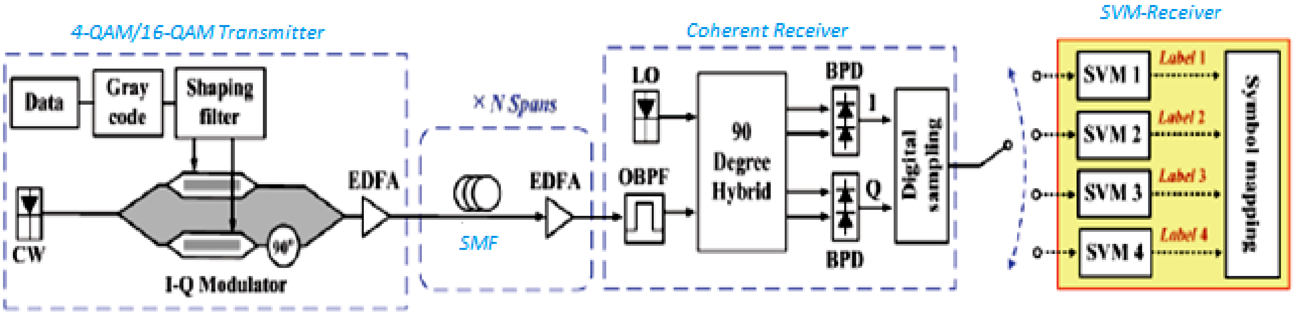


Fig. 1. The schematic diagram of the proposed coherent optical OFDM incorporating the SVM equalizer in the receiver

The received symbols for each subcarrier x{k} are processed by the Nonlinear Equalizer (NLE) supported vectors which are scaled by weight values (i.e. the Lagrange multipliers) for each subcarrier wk, i, after which, the outputs for different k are summed.

Fig.1 illustrates the schematic diagram of the proposed coherent optical OFDM incorporating the SVM equalizer in the receiver where CP is Cyclic Prefix, DAC is Digital-to-Analogue Converter, MZM is Mach-Zehnder Modulator, SMF is Single Mode Fiber, EDFA is Erbium Doped Fiber Amplifier, LPF is Low-Pass Filter, ADC is Analogue-to-Digital Converter, BER is Bit-Error-Rate, FFT is Fast Fourier Transform and IFFT is Inverse Fast Fourier Transform. In addition, SMF is Single Mode Fiber, EDFA is Erbium Doped Fiber Amplifier.

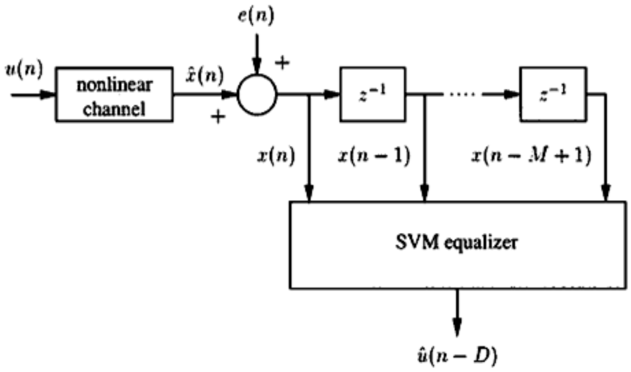


Fig. 2. Model of the nonlinear transmission system from Chen et al. [15]

The proposed signal model for novel OFDM-SVM is as follows:

$$r_n = \sum_k X_k H_k e^{j\frac{2\pi kn}{N}} + e_n \qquad (4)$$

where X_k is the data symbol transmitted at the kth subcarriers.

e_n contains the residual noise. In order to improve the performance of the estimation algorithm, a robust cost function must be introduced instead of the Maximum likelihood (ML) criterion.

SVM algorithms minimize a regularized cost function of the residuals. In [3], the ε-Huber cost function is used, given by

$$L(e_n) = \begin{cases} 0 & |e_n| \le \varepsilon \\ \frac{1}{2\delta}(|e_n| - \varepsilon)^2 & \varepsilon \le |e_n| \le e_C \\ C(|e_n| - \varepsilon) - \frac{1}{2}\delta C^2 & |e_n| \ge e_C \end{cases} \qquad (5)$$

where $e_C = \varepsilon + \delta C$, ε is the insensitive parameter, and δ and C control the trade-off between the regularization and the losses. Here, for complex e_n, we define $L(e_n)$. The primal problem can be stated as minimizing

$$\frac{1}{2}\sum_k |H_k|^2 + \frac{1}{2\delta}\sum_{n\in I_1}(\xi_n + \xi_n^+)^2 + C\sum_{n\in I_2}(\xi_n + \xi_n^+)^2 + \frac{1}{2\delta}\sum_{n\in I_3}(\xi_n + \xi_n^+)^2 + \sum_{n\in I_4}(\xi_n + \xi_n^+)^2 - \frac{1}{2}\sum_{n\in I_3, I_4}\delta C^2 \qquad (6)$$

constrained to

$$R\{r_n\} - \sum_k R(X_k H_k e^{j\frac{2\pi kn}{N}}) \le \varepsilon + \xi_n \qquad (7)$$

$$I\{r_n\} - \sum_k I(X_k H_k e^{j\frac{2\pi kn}{N}}) \le \varepsilon + \xi_n \qquad (8)$$

$$-R\{r_n\} + \sum_k R(X_k H_k e^{j\frac{2\pi kn}{N}}) \le \varepsilon + \xi_n \qquad (9)$$

$$I\{r_n\} - \sum_k I(X_k H_k e^{j\frac{2\pi kn}{N}}) \le \varepsilon + \xi_n^+ \qquad (10)$$

$$\xi_n, \xi_n^+ \ge 0 \qquad (11)$$

For $n = 0,\dots, N-1$, where pairs of stack variables are introduced for both real (ξ_n^+) and imaginary (ξ_n^+) residuals; superscript + and no superscript stand for positive and negative components of residuals.

$I_1 - I_2(I_3 - I_4)$ are the set of samples for which real (imaginary) parts of the residuals are in the quadratic-linear cost zone.

$I1$,2,$I3$ and $I4$ are the set of samples for which:

$I1$: real part of the residuals are in the quadratic zone;

$I2$: real part of the residuals are in the linear zone;

$I3$: imaginary part of the residuals are in the quadratic zone;

$I4$: imaginary part of the residuals are in the linear zone.

The derivation of a similar dual problem can be found in [3]-[4], and only the new steps that are specific to our proposal are pointed out next. In brief, the primal-dual functional is obtained by introducing the constraints into the primal functional by means of Lagrange multipliers $\{\alpha_{R,n}\}$, $\{\alpha_{R^+,n}\}$, $\{\alpha_{I,n}\}$, $\{\alpha_{I^+,n}\}$ for the real (subscript R) and imaginary (subscript I) parts of the residuals. By making zero the primal-dual functional gradient with respect to H_k, we have the following expression for channel estimated values at pilot positions:

$$\tilde{H}_k = \sum_{n=0}^{N-1} \Psi_n X_k \qquad (12)$$

where $\Psi_n = (\alpha_{R,n} - \alpha_{R,n}^+) + j(\alpha_{I,n} - \alpha_{I,n}^+)$.

For notation, we define the following column vector :

$$v_n(k) = [X_k e^{j\frac{2\pi kn}{N}}] \qquad (13)$$

and the following Gram matrix as $R(n,m) = v_n^H v_m$ by placing optimal solution (13) into the primal-dual functional and grouping terms, a compact form of the functional problem can be stated in vector form, which consists of maximizing

$$\frac{1}{2}\Psi^H(R + \delta I)\Psi + R(\Psi^H r) - (\alpha_R + \alpha_R^+ + \alpha_I + \alpha_I^+)1\varepsilon \qquad (14)$$

constrained to

$$0 \le \left\{\alpha_{R,n}\right\},\left\{\alpha^{+}_{R,n}\right\},\left\{\alpha_{I,n}\right\},\left\{\alpha^{+}_{I,n}\right\} \le C \qquad (15)$$

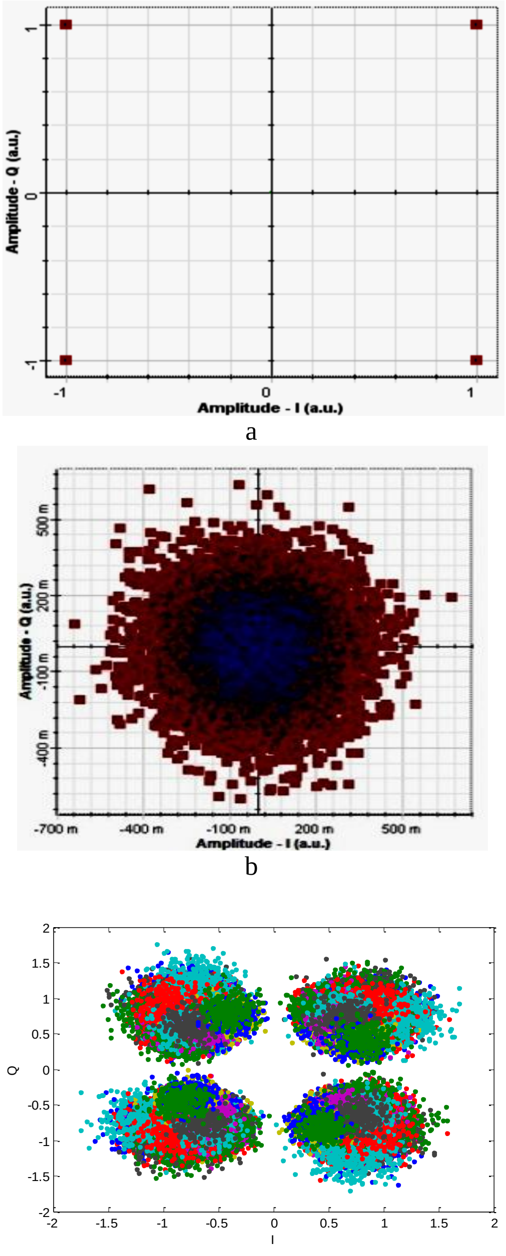
Where $\Psi = [\Psi_0,\ldots,\Psi_{N-1}]^T$; I,1 are the identity matrix and the all-ones column vector, respectively; α_R is the vector containing the corresponding Lagrange multipliers, with the other subsets being similarly represented; and $r = [r_0,\ldots,r_{N-1}]^T$. Note that (14) is a quadratic form and, thus, real-valued, and it represents a natural extension of the dual functional in SVM real regression for complex-valued problems. The channel values at pilot positions (13) can be obtained by optimizing (14) with respect to $\{\alpha_{R,n}\}$, $\{\alpha_{R^+,n}\}$, $\{\alpha_{I,n}\}$, $\{\alpha_{I^+,n}\}$ and then substituting into (13) active layer.

This paper, we propose a novel blind SVM equalizer (B-SVM) for 16-quadrature amplitude modulation (16-QAM) CO-OFDM based on the minimization of the cost function of the SVM with the classical Sato's error functions for blind equalization. It is shown that in 40-Gb/s 16-QAM CO-OFDM at 2000 km of transmission, B-SVM-NLE presents ~1dB reduction in fiber nonlinearity penalty compared to 40-Gb/s CO-OFDM non-blind Volterra-based nonlinear equalizer.

3. Results and discussions

For the numerical investigations, the developed OFDM transceivers, as well as the optical transmission, was implemented with the help of Matlab/Optisystem co-simulated environment. In which, Matlab tool is used for electrical domain and Optisystem for optical components with a standard single mode fiber (SSMF).

This proposed experimental setup shown in Fig. 1. Demonstrates a 100-Gb/s data rate CO-OFDM modem signals, an NRZ baseband signal running at 100-Gb/s (i. e. PRBS). The bit sequence (PRBS) length of 2^{31}-1. CW Laser which is operating at wavelength λ_1 equal 1550nm. CW-laser is characterized with a line width equal to 0.1 MHz. The bit stream is generated by a PRBS generator and mapped by a 4-Quadrature Amplitude Modulation (4-QAM) encoder. The resulting signal is modulated by an OFDM modulator which having a number of 104 subcarriers position array equal to 12, a number of Fast Fourier Transform (FFT) points equal to 128 and number of prefix point equal to 14. After that, the resulting electrical signal is modulated to the optical signal using a pair of Mach-Zehnder Modulators (MZM). The signal after the two MZMs is transmitted via a loop SMF of length 100 km on each span which is mostly used for practical application.



c

Fig. 3. Constellation diagram for CO-OFDM a) at the transmitter, b) over 1600km fiber without SVM equalizer c) over 1600km fiber with SVM equalizer for 1000 symbols which corresponds to different colors

The attenuation of SMF is compensated by in-line optical amplifiers (EDFA). These EDFAs have a gain of 13 dB and noise figure equal to 4 dB. The chromatic dispersion (CD) parameters for SMF at 1550nm are 16.75 ps/nm/km and 0.075ps/nm^2/km (CD slope). The SVM equalizer is placed after the coherent detection in the frequency domain. Nonetheless, for coherent optical OFDM performance consideration, it is very helpful to use a constellation diagram. The constellation diagram describes the signal that digitally modulated, presenting it as a two-dimensional dispersion diagram. Fig. 3 a) displays a pure electrical constellation scheme for the signal transmission for 4-QAM digital modulator with 2 bits at the transmitter. Constellation diagrams can measure the distortion and interference in a signal. As shown in Fig. 3b), the constellation of the 4QAM signal for a CO-OFDM system at the receiver without SVM equalizer when the length of the fiber is 1600 km. Fig. 3 c) displays the constellation of the 4QAM signal for CO-OFDM at the receiver including the SVM equalizer using a fiber length equal to 1600 km.

As depicted in Fig. 3a), the signal begins to become indistinct because nonlinear effects when it is compared with the transmission signal. In addition, the blue points describe the noise caused by the laser and the red points represent the signal.

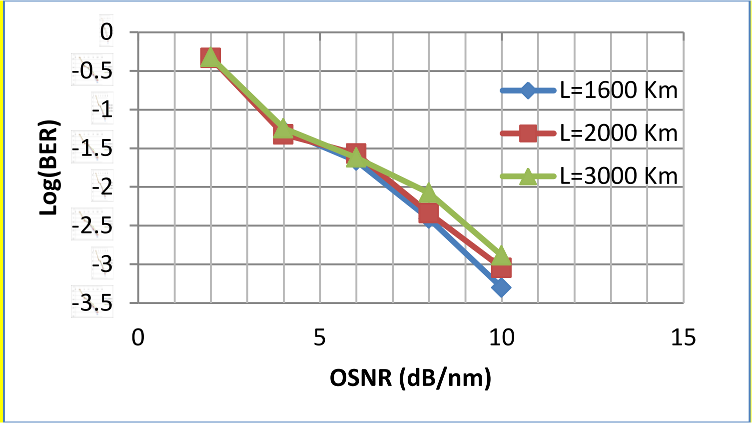


Fig. 4. BER of 4-QAM CO-OFDM systems with SVM nonlinear equalization as a function of OSNR (fixed laser launch)

Fig. 4 displays the effect of the OSNR on the BER of the system for the targeted transmission distances of which is 1600, 2000 and 3000 km. As shown from Fig.4. increasing the OSNR will maintain BER value less than 10^{-3}. When comparing Fig.4. with Fig.5. which shows the BERs of OFDM systems with no compensation and with linear, Volterra, and Wiener-Hammerstein equalization at different OSNR under 1 dBm laser launch power. As a result, the outperformance of nonlinear SVM equalizer according to Fig. 5 has the best performance compared to Volterra and Hammerstein equalizer for a fixed launch power.

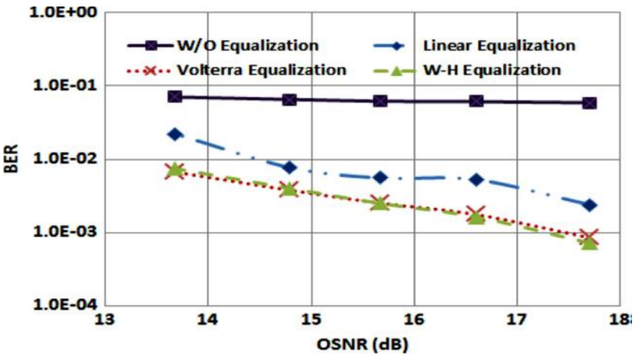


Fig. 5. BER of 16-QAM CO-OFDM systems without compensation and with linear/nonlinear equalization as a function of OSNR (fixed laser power) [14]

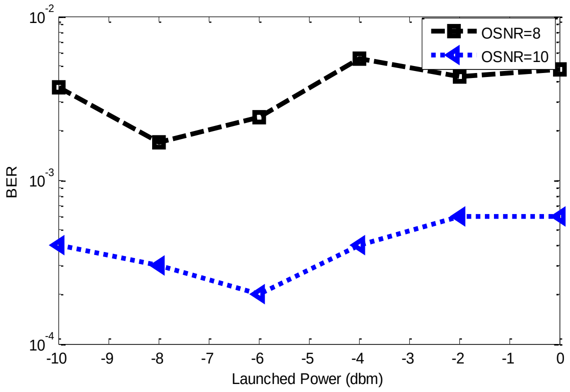


Fig. 6. BER of 4-QAM CO-OFDM systems with SVM nonlinear equalization as a function of laser launch power

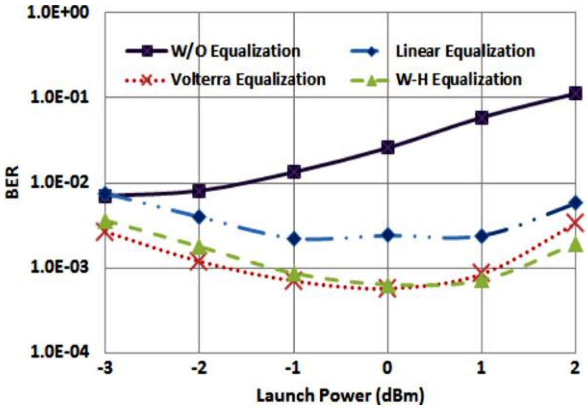


Fig. 7. BER of 16-QAM CO-OFDM systems without compensation and with linear/nonlinear compensation as a function of laser launch power [14]

The SVM equalizer can offer a 7.75 dB improvement in optical signal-to-noise ratio (OSNR) compared to Volterra algorithm for 100 Gbit/s CO-OFDM signals when considering only nonlinearities to achieve a Bit-Error-Ratio inferior to 10E-3. It is also revealed that SVM can double the transmission distance up to 1600 km over SMF compared to the case of Volterra and Hammerstein.

All simulation parameters are summarized in the Table.1.

Table.1 Simulation parameters

Parameters	value
Wavelength	1550.2 nm
Fiber span	100 Km
Attenuation	18.9-19.5 dB/100 km
ECL linewidth	100 KHz
OFDM symbols	400
Nonlinear Kerr coefficient	$2{:}6{*}10^{-20}$ m^2W^{-1}
IFFT point	512
Modulation	16-QAM
Cyclic Prefix	2%
Bit rate	40 Gb/s

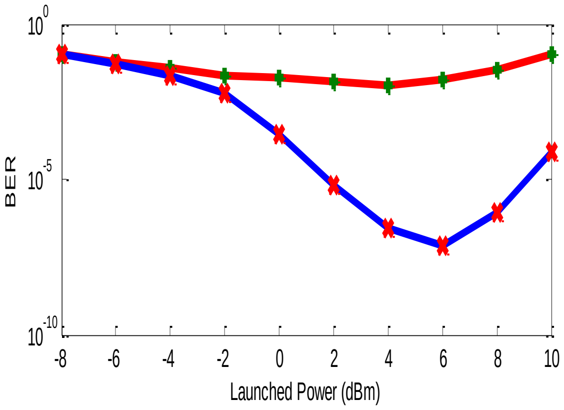


Fig. 8. BER vs Launched Optical Power (LOP¨) for 40 Gb/s coherent Optical OFDM based Non-Blind SVM Equalizer Red line (W/O equalizer), Blue line (Non-Blind SVM Equalizer)

In Fig. 8. BER vs Launched Optical Power (LOP¨) for 40 Gb/s coherent Optical OFDM based Non-Blind SVM Equalizer is plotted. For 16-QAM, a FEC-limit results in a BER of 3.8*10E-3 (Q-factor of ~9.8 dB). In Fig. 3, the BER against the LOP is plotted for 40-Gb/s CO-OFDM at 2000 km with and without (w/o) Non-Blind SVM. It is shown that the nonlinearity penalty is reduced by ~1 dB at optimum 2 dBm of LOP. The inset 16-QAM constellations corroborate SVM performance enhancement.

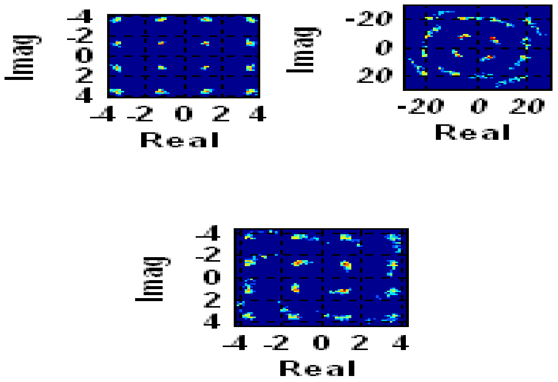


*Fig. 9. a-B2B Constellation; **b**- W/O Equalization Constellation **c**-NB-SVM equalization Constellation*

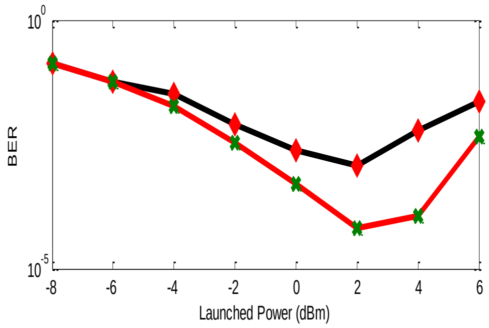


Fig. 10. BER vs Launched Optical Power (LOP¨) for 40 Gb/s coherent Optical OFDM based Blind SVM Equalizer Black line (Volterra equalizer), Red Line (Blind SVM Equalizer)

In Fig. 10. BER vs Launched Optical Power (LOP¨) for 40 Gb/s coherent Optical OFDM based Blind SVM Equalizer is plotted. For 16-QAM, a BER of 10-3 (FEC-limit) results in a BER of 3.8*10E-3 (Q-factor of ~9.8 dB). In Fig. 4, the BER against the LOP is plotted for 40-Gb/s CO-OFDM at 2000 km with Non-Blind SVM and Volterra equalizers. It is shown that the nonlinearity penalty is reduced by ~1 dB at optimum 2 dBm of LOP.

4. Conclusions

In this paper, a long-haul Coherent Optical OFDM Signal transmission system is successfully demonstrated with Support Vector Machine equalization. Furthermore, the nonlinear effect resistance and transmission up to 3000 km can be enhanced compared to the Volterra based CO-OFDM which is limited to 800 km. Nonetheless, SVM can be considered as a robust nonlinearity compensation technique. Finally, it is worth noting that this work should trigger the implementation of nonlinear SVM-based equalizers in new generation core networks. Also, We have implemented a B-SVM-based NLE, in 40 Gbps 16-QAM CO-OFDM with Blind and Non-Blind SVM equalizers. We have evaluated the performance of B-SVM in different launched power levels at 2000 Km fiber length by numerical simulations and compared it with the benchmark Volterra nonlinear equalizer. It was shown that B-SVM reduced the nonlinearity penalty by about 1 dB at 2000 km of transmission compared to Volterra. Also this nonlinearity penalty is reduced by ~7 dB at optimum 4 dBm of LOP when using SVM-NLE.

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