Reduction of Nonlinear Intersubcarrier Intermixing in Coherent Optical OFDM by a Fast Newton-Based Support Vector Machine Nonlinear Equalizer

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***Abstract*—A fast Newton-based support vector machine (N-SVM) nonlinear equalizer (NLE) is experimentally demonstrated, for the first time, in 40 Gb/s 16-quadrature amplitude modulated coherent optical orthogonal frequency division multiplexing at 2000 km of transmission. It is shown that N-SVM-NLE extends the optimum launched optical power by 2 dB compared to the benchmark Volterra-based NLE. The performance improvement by N-SVM is due to its ability of tackling both deterministic fiber-induced nonlinear effects and the interaction between nonlinearities and stochastic noises (e.g., polarization-mode dispersion). An N-SVM is more tolerant to intersubcarrier nonlinear crosstalk effects than Volterra-based NLE, especially when applied across all subcarriers simultaneously. In contrast to the conventional SVM, the proposed algorithm is of reduced classifier complexity offering lower computational load and execution time. For a low *C*-parameter of 4 (a penalty parameter related to complexity), an execution time of 1.6 s is required for N-SVM to effectively mitigate nonlinearities. Compared to conventional SVM, the computational load of N-SVM is ∼6 times lower.**

***Index Terms*—Coherent detection, coherent optical OFDM, nonlinearity mitigation, support vector machines.**

I. INTRODUCTION

THE data rate in an optical transmission system is currently limited by amplified spontaneous emission, which determines the minimum power launched into each fiber span, and the interplay between chromatic dispersion (CD) and Kerr fiber nonlinearity, which limits the maximum launch power [1].

To increase the data rate of current-generation coherent systems, fiber nonlinearity compensation is required to enable higher launch powers, thereby providing enough optical signal-to-noise ratio to support larger constellation sizes [2]. State-of-the-art fiber nonlinearity compensators (NLC) include digital signal processing (DSP)-based techniques such as digital back-propagation (DBP) [2], [3], reduced complexity Volterra-based nonlinear equalization (NLE) [4], and phase-conjugated twin-waves [5], which tackle nonlinearities of deterministic nature. However, in coherent long-haul optical systems the interaction between nonlinear phenomena with random noises such as polarization-mode dispersion (PMD) results in stochastic nonlinear distortion, which can be partially mitigated using machine learning in the digital domain such as support vectors machines (SVM) [6]–[10].

On the other hand, coherent optical orthogonal frequency division multiplexing (CO-OFDM) is an excellent candidate for long-haul communications because of its high spectral efficiency, flexibility, and tolerance to chromatic dispersion (CD) and PMD. However, due to its high peak-to-average power ratio the deterministic nonlinear cross-talk effects among subcarriers such as inter-subcarrier intermixing (ICI) cross-phase modulation (XPM) and four-wave mixing (FWM) are significantly enhanced causing an additional “stochastic-like” interference [6], [7]. SVM-based NLEs [6]–[10] have shown promising results in CO-OFDM. Nevertheless, since optimization usually requires many steps to converge (in the order of 30) [7], implementation in real-time processing is impractical.

In this paper, we experimentally demonstrate, for the first time, a fast classification SVM-NLE of reduced classifier complexity using the Newton-method (N-SVM) [11] in 16 quadrature amplitude modulated (16-QAM) CO-OFDM at 40 Gb/s, transmitted at 2000 km of standard single-mode fiber (SSMF). It is shown that compared to the benchmark deterministic Volterra-based NLE, N-SVM extends the optimum launched optical power (LOP) by 2 dB with very low DSP computational load and execution time. N-SVM tackles ICI nonlinear crosstalk effects more effectively than Volterra-NLE especially when

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Manuscript received December 30, 2016; revised February 23, 2017; accepted March 1, 2017. Date of publication March 7, 2017; date of current version April 20, 2017. This work was supported in part by the Centre of Excellence (CUDOS, CE110001018), in part by the EPSRC (EP/J017582/1, EP/L000091/1, EP/M005283/1), and in part by the Sterlite Technologies Ltd.

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Digital Object Identifier 10.1109/JLT.2017.2678511

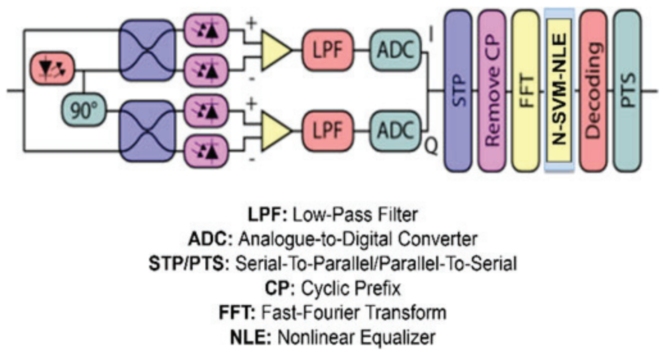

Fig. 1. Block diagram of the CO-OFDM receiver equipped with the proposed N-SVM-NLE.

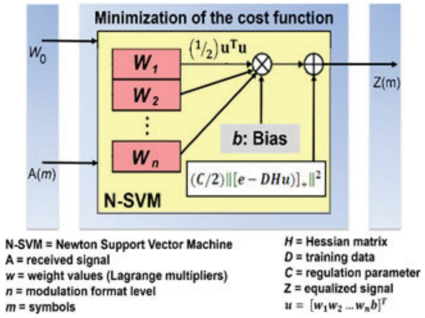

Fig. 2. Block diagram of proposed N-SVM for the adopted single-channel/polarization 16-QAM CO-OFDM receiver.

applied across all subcarriers simultaneously, rather than on each subcarrier separately.

The paper is organized as follows: Section II analyses the principle of the proposed N-SVM-NLE and the benchmark Volterra-NLE for 16-QAM CO-OFDM. Section III describes the experimental CO-OFDM setup. Section IV presents the experimental results of N-SVM-NLE and Volterra-NLE for CO-OFDM at 2000 km of transmission, and finally in Section V the paper is concluded.

II. PRINCIPLE OF NEWTON SUPPORT VECTOR MACHINE-NLE

A. *Operation of N-SVM-NLE for 16-QAM CO-OFDM*

In Fig. 1 the block diagram of the CO-OFDM receiver equipped with the N-SVM-NLE is depicted, where the received optical signal is converted back to an electrical one through a homodyne 90° coherent detector. Afterwards, OFDM demodulation process follows similarly to [6], where serial-to-parallel (STP), removal of cyclic prefix (CP) and fast Fourier transform (FFT) are processed. After the FFT block the proposed N-SVM-NLE takes place for all subcarriers simultaneously before decoding and parallel-to-serial (PTS) conversion. The proposed N-SVM-NLE implements a fast Newton method that suppresses input space features for a nonlinear programming formulation of supervised SVM classifiers. This stand-alone method can handle classification problems in very high dimensional spaces. An implicit Lagrangian formulation of an SVM classifier which leads to a highly effective iterative scheme [11] is solved in this algorithm by a Newton method which handles classification problems in just a few steps. In order to handle a 16-QAM constellation mapper which has a very large dimensional input, a fast-finite Newton method is employed to find the unconstrained unique global minimum solution of the implicit Lagrangian associated with the classification problem. The solution is obtained by solving a system of nonlinear equations, a finite number of times. The algorithm implements the Newton method with an Armijo step-size [12] and establishes its finite global termination to the unique solution. All vectors are column vectors unless transposed to a row vector by a T superscript. The 2-norm of a vector x is denoted by x. The matrix A[m × n] is related to the *A* received signal with *m* complex OFDM symbols in the *n*-dimensional real space R^m which defines the order of modulation format level (i.e. 16 for 16-QAM) as depicted in Fig. 2.

In Fig. 2 where *e* is the column vector of value 1, while *w*, *b*, are the normal vector (i.e. weights with w_0 being the initialized weight) and the scalar of the hyperplane (bias), respectively. To control the trade-off between minimizing training errors and model complexity we introduce a slack variable *z* for each training symbol and a "penalty parameter" *C* (which controls the trade-off between the slack variable penalty and the margin). Similar to [13] the margin maximization formula in the SVM is replaced by the least square 2-norm error, which brings out an unconstrained optimization being solved by the finite "stepless" Newton method. The N-SVM formulation thus requires only solutions of nonlinear equations instead of quadratic programming and simultaneously maximizes the margin and minimizes the error as shown in (1):

$$\min\ f(w,b,z) = \left(\frac{1}{2}\right)\|w\|^2 + Ce^T z$$
$$\text{subject to}\ \ D(Aw-eb)|+z \geq e, \tag{1}$$

where $z \in R^m$ is the non-negative slack vector and $C \in R^1$ is a positive constant (*C* penalty parameter), both used to tune errors and margin size, while *A* is the received signal. To perform nonlinear N-SVM, the classification sigmoid function is employed. To change from a linear to a non-linear classifier however, we substitute a kernel evaluation in (1) instead of the original 'dot product'. Recent developments for massive nonlinear SVM algorithms [11] reformulate the classification as an unconstrained optimization. By changing the margin maximization to the minimization of $(\frac{1}{2})w, b^2$ and adding with a least squares 2-norm error, the SVM reformulation with nonlinear kernel leads to:

$$\min\ f(w,b,z) = \left(\frac{1}{2}\right)\|w,b\|^2 + \left(\frac{C}{2}\right)\|z\|^2$$
$$\text{subject to}\ D(Aw-eb)+z \geq e \tag{2}$$

The formulation of (2) can be rewritten by substituting $z = [e - D(Aw-eb)]_+$ leading to (3):

$$\min\ f(w,b) = \left(\frac{1}{2}\right)\|w,b\|^2 + \left(\frac{C}{2}\right)\left\|[e-D(Aw-eb)]_+\right\|^2 \tag{3}$$

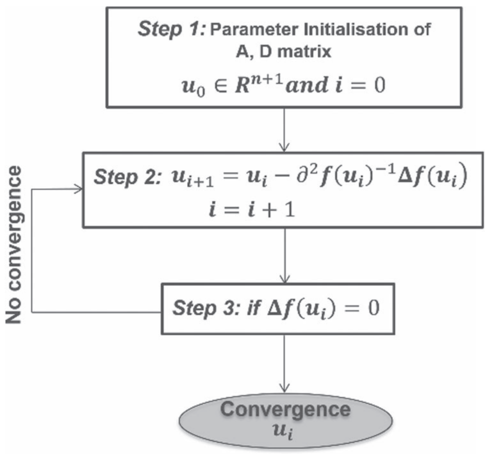

Fig. 3. N-SVM algorithm. A = Received signal; D = training data.

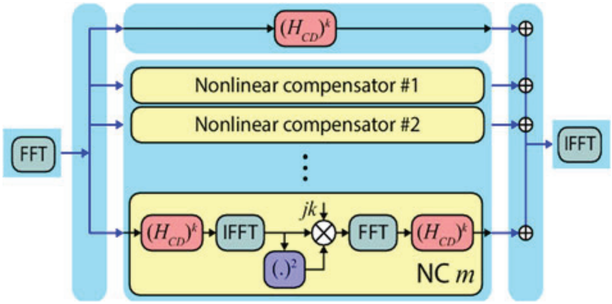

Fig. 4. IVSTF-NLE [4] for 16-QAM CO-OFDM. (I)FFT: (inverse) fast-Fourier transform; H_{CD}: system chromatic dispersion; NC: nonlinearity compensation; *k*: constant related to the nonlinear distortion and the total power. *m*: number of nonlinearity compensators.

where $(x)_+$ replaces negative components of a vector *x* by zeros into the objective function *f*. By setting $[w_1 w_2 \ldots w_n b]^T$ to u and $[A - e]$ to *H* (which is the Hessian matrix [11]), then the SVM formulation of (3) is rewritten by (4):

$$\min f(w, b) = \left(\frac{1}{2}\right) u^T u + \left(\frac{C}{2}\right) \left\|[e - DHu)]_+\right\|^2 \quad (4)$$

B. The "Stepless" N-SVMA Algorithm

The adopted N-SVM process is described in Fig. 3 showing the finite "stepless" Newton method which solves the strongly convex unconstrained minimization problem in (4). In most of tested cases [11]–[14] this algorithm has given an optimum solution with a few number of iterations varying from 5 to 8.

III. BENCHMARK VOLTERRA-NLE FOR 16-QAM CO-OFDM

The adopted Volterra-NLE is similar to [4], accounting for single-band and single-polarization as depicted in Fig. 4. It employs the inverse Volterra-series transfer function (IVSTF) with up to 3rd order Volterra kernels. It should be noted that when higher-order kernels were employed, similar results were revealed [15]. IVSTF-NLE offers ~25% reduced complexity compared to full-step/span DBP [4], [9] and inherits some of the features of the hybrid time-and-frequency domain implementation, such as non-frequency aliasing and simple implementation.

The process of nonlinearity compensation by Volterra-NLE is described as follows: The input OFDM signal is first converted to frequency domain by FFT. The Volterra-NLE compensates CD using a linear compensator.

On the other hand, the number of required nonlinear compensators depends on the number of homogeneous spans in the transmission link. The output of the linear and nonlinear compensator is combined and converted back to time-domain using the inverse FFT (IFFT). The Volterra-NLE procedure can be described from (5)–(9). Since a reduced complexity 3rd order IVSTF is considered, the kernels $H_1(\omega, z)$ and $H_3(\omega_1, \omega_2, \omega - \omega_1 + \omega_2, z)$ are given by,

$$H_3(\omega z) = e^{-\alpha z/2} e^{-j\omega^2 \beta_2 z/2} \quad (5)$$

$$H_3(\omega_1, \omega_2, \omega - \omega_1 + \omega_2, z) = -\frac{j\gamma}{4\pi^2} H_1(\omega, z) \times \frac{1 - e^{-(\alpha + j\beta_2(\omega_1 - \omega)(\omega_1 - \omega_2))z}}{\alpha + j\beta_2(\omega_1 - \omega)(\omega_1 - \omega_2)}. \quad (6)$$

where ω is the optical frequency and ω_1, ω_2 are the dummy variables acting as parameters and influence the interactions of the lightwaves at different frequency, especially the ICI interaction effects. α is the fiber loss, β_2 is the 2nd order CD parameter and γ accounts for the effect of fiber nonlinearity averaging. For an optically amplified Nspan fiber link with Lspan being the span length, the corresponding p^{th} inverseis given by the nonlinear kernels as,

$$K_1(\omega) = H_1^{-1}(\omega) = e^{-j\omega^2 \beta_2 N_{span} L_{span}/2} \quad (7)$$

$$K_3(\omega_1, \omega_2, \omega - \omega_1 + \omega_2) = -\frac{j\gamma}{4\pi^2} K_1(\omega) \times \frac{1 - e^{-(\alpha + j\beta_2 \Delta\omega) L_{span}}}{\alpha + j\beta_2(\omega_1 - \omega)(\omega_1 - \omega_2)} \sum_{k=1}^{N_{span}} e^{-jk\beta_2 L_{span}\Delta\omega} \quad (8)$$

$$\approx -\frac{j\gamma}{4\pi^2} \times \frac{1 - e^{-\alpha L_{span}}}{\alpha} \times K_1(\omega) \sum_{k=1}^{N_{span}} e^{-jk\beta_2 L_{span}\Delta\omega}. \quad (9)$$

The corresponding compensation scheme representing (7) and (9) is applied in Fig. 4. Each nonlinear compensation stage is a realization of

$$K_3(\omega_1, \omega_2, \omega - \omega_1 + \omega_2) \approx -\frac{j\gamma}{4\pi^2} \times \frac{1 - e^{-\alpha L_{span}}}{\alpha} \times K_1(\omega) e^{-jk\beta_2 L_{span}\Delta\omega}. \quad (10)$$

Finally, since single-polarization is considered we have

$$S_{K_1}(\omega) \iint_{\infty}^{\infty} K_{3,K_1}(\omega_1, \omega_2, \omega - \omega_1 + \omega_2) \times A(\omega_1) A^*(\omega_2) \times A(\omega - \omega_1 + \omega_2) d\omega_1 d\omega_2 \quad (11)$$

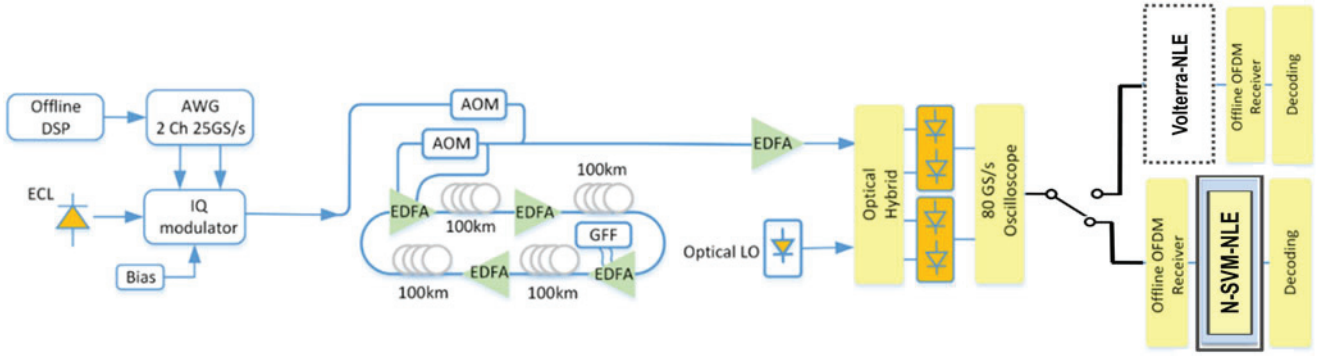

Fig. 5. Experimental setup of 40 Gb/s CO-OFDM equipped with either Volterra-NLE or N-SVM-NLE. ECL: external cavity laser, DSP: digital signal processing, AWG: arbitrary waveform generator, AOM: acousto-optic modulator, EDFA: Erbium-doped fiber amplifier, GFF: gain flatten filter, LO: local oscillator.

where $S_{K_1}(\omega)$ is derived by passing the received signal through $(H_{CD})^{(K_1,K_2)}$, and nonlinearity compensation is performed by $jk(|.|^2)(.)$ where we multiply the received signal by a constant k related to the nonlinear distortion and the total power. This parameter varies for this configuration and is obtained by sweeping it to get optimum performance, which is part of the calibration of the Volterra-NLE. Finally, the residual CD is compensated passing through $(H_{CD})^{N-(K_1,K_2)}$.

IV. EXPERIMENTAL SETUP

Fig. 5 depicts the experimental setup where an external cavity laser (ECL) of 100 kHz linewidth was modulated using a dual-parallel Mach-Zehnder modulator (DP-MZM) in IQ configuration. The DP-MZM was fed with OFDM I-Q components, which was generated offline. The transmission path at 1550.2 nm was a recirculating loop consisting of 20×100 km spans of Sterlite OH-LITE (E) SSMF (attenuation of 18.9-19.5 dB/100 km) controlled by acousto-optic modulator (AOM). The loop switch was located in the mid-stage of the 1st Erbium-doped fiber amplifier (EDFA) and a gain-flattening filter (GFF) was placed in the mid-stage of the 3rd EDFA. The optimum LOP was swept by controlling the output power of the EDFAs. At the receiver, the incoming signal was combined with another 100 kHz linewidth ECL acting as local oscillator. After down-conversion, the baseband signal was sampled using a real-time oscilloscope operating at 80 GS/s and processed offline in *Matlab*. 400 OFDM symbols were generated using a 512-point IFFT in which 210 subcarriers were modulated using 16-QAM. To eliminate inter-symbol-interference from linear effects, a CP of 2% was included. For fair comparison among linear equalization (LE), Volterra-NLE and the proposed N-SVM-NLE, the net and raw bit-rate were fixed at ~40 Gb/s and ~46 Gb/s, respectively. The N-SVM training overhead was set at 10% (optimum value for LE) resulting in a training length of 40 symbols. The offline OFDM demodulator included timing synchronization, frequency offset compensation, channel estimation and equalization with the assistance of an initial training sequence, as well as I-Q imbalance and CD compensation using an overlapped frequency domain equalizer employing the overlap-and-save method. When N-SVM-NLE was performed, the LE was neglected due to N-SVM ability of compensating both linear and nonlinear inter-subcarrier crosstalk effects. The CO-OFDM transceiver and transmission parameters are depicted on Table I. The NLEs performances were assessed by Q-factor measurements averaging over 10 recorded traces (~10^6 bits), which was estimated from the bit-error-rate (BER) obtained by error counting after hard-decision decoding. The Q-factor is related to BER by $Q = 20\log_{10}[\sqrt{2}erfc^{-1}(2BER)]$. For 16-QAM, a BER of 10^{-3} (forward-error-correction-limit, FEC-limit) results in a Q-factor of ~9.8 dB.

TABLE I
CO-OFDM TRANSCEIVER AND TRANSMISSION PARAMETERS

Parameter	Value
Net bit-rate (LE, NLEs)	~40 Gb/s
Raw bit-rate (LE, NLEs)	~46 Gb/s
Signal modulation format	16-QAM
OFDM symbols	400
Modulated OFDM subcarriers	210
Cyclic prefix (CP) length	2%
FFT/IFFT size	512
N-SVM Training overhead	10%
N-SVM Training symbol length	40 symbols
ECL linewidth	100 KHz
OH-LITE (E) SSMF attenuation	18.9–19.5 dB/100 km
Span number	20
Span length	100 km
Transmission wavelength	1550.2 nm

V. RESULTS AND DISCUSSION

In Fig. 6 the Q-factor against the training overhead of N-SVM-NLE is depicted for 16-QAM CO-OFDM at 2000 km of transmission for a LOP of 2 dBm, which is the optimum LOP of LE. It should be noted that changing the training overhead, the raw bit-rate was adjusted accordingly. From Fig. 6 it is evident that a minimum 10% of training data is required for N-SVM-NLE to effectively tackle the OFDM inter-subcarrier crosstalk effects (e.g. ICI-XPM/FWM). In this paper, 10% of training data are employed for N-SVM-NLE in all sections.

In Fig. 7, the Q-factor against the LOP is plotted for the 40 Gb/s CO-OFDM system at 2000 km of transmission for LE, Volterra-NLE, and N-SVM-NLE. It is shown that compared to Volterra-NLE, the proposed N-SVM-NLE can extend the

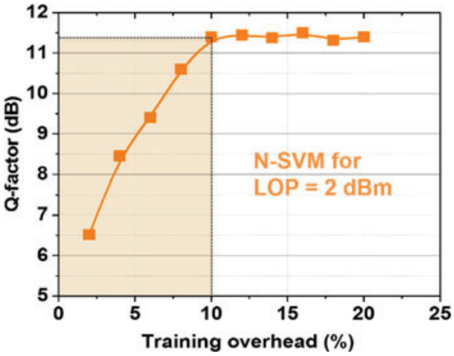

Fig. 6. Q-factor vs. training overhead of N-SVM-NLE for 16-QAM CO-OFDM at 2000 km of transmission for a launched optical power (LOP) of 2 dBm, which is the optimum LOP of linear equalization (LE).

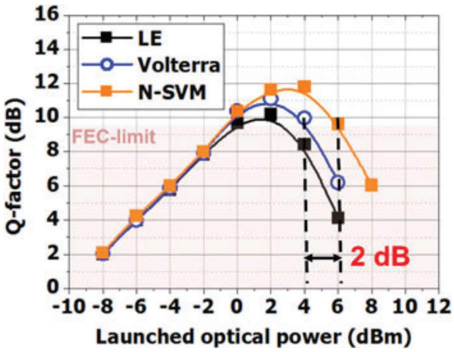

Fig. 7. Q-factor vs. LOP for 16-QAM CO-OFDM when performing LE, Volterra-NLE, and N-SVM-NLE.

optimum LOP by 2 dB (FEC-limit at ∼9.8 dB), while in comparison to LE it can extend the LOP by ∼3.5 dB. To corroborate the N-SVM-NLE performance enhancement, Fig. 8 is plotted, showing the received 16-QAM constellations diagrams for the three types of equalization and without equalization at 6 dBm of LOP.

In Fig. 9, the Q-factor against the *C*-parameter (the *C* value from (2)) is plotted for the CO-OFDM system under test at a LOP of 4 dBm. The *C*-parameter (also called "penalty parameter") is related to the computational complexity of N-SVM. It is shown that a *C* of only 4 is required at an execution time of 1.6 sec for stable optimum performance. This time required by the training process is considered for a general-purpose CPU operating at 1.2 GHz. However, this time will be drastically reduced in implementations based on Field-Programmable Gate-Array or Application Specific Integrated Circuits. The minimum required *C* value for N-SVM-NLE is ∼6 times less than the corresponding "penalty parameter" of the conventional SVM-NLE reported in [7] for 16-QAM CO-OFDM. This occurs because i) N-SVM performs fast classification tasks that separate cases of different class labels, and ii) the conventional SVM performs both classification and regression analysis in contrast to N-SVM which only classifies the data. It should be noted that a transmission performance comparison between the proposed N-SVM and the conventional SVM [7] is out of the scope of this paper since fair comparison is not feasible.

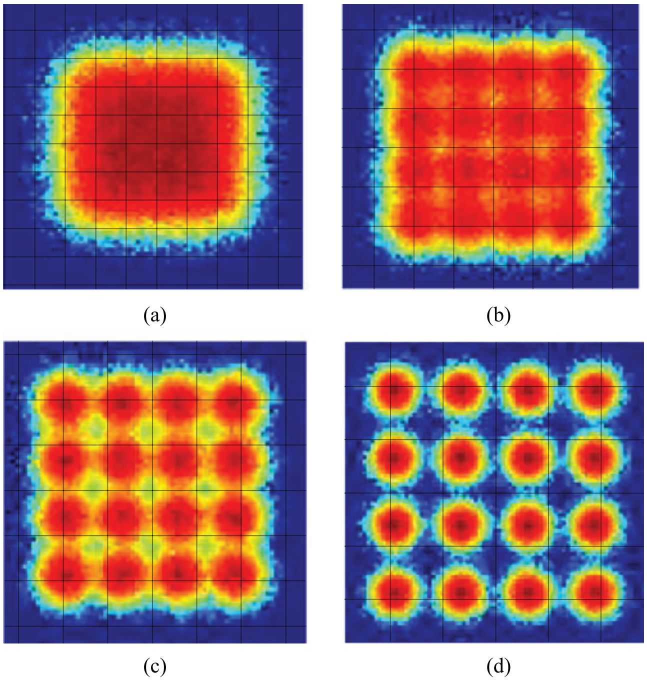
(a) (b)
(c) (d)

Fig. 8. Received 16-QAM constellation diagrams of CO-OFDM at 2000 km of transmission when the LOP is 6 dBm for the following cases: (a) without equalization, (b) LE, (c) Volterra-NLE, and (d) N-SVM-NLE.

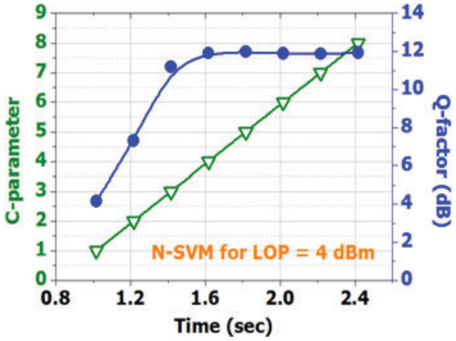

Fig. 9. C-parameter/Time vs. Q-factor for 16-QAM CO-OFDM equipped with N-SVM-NLE at a LOP of 4 dBm.

In Fig. 10 the impact of N-SVM on the nonlinear ICI crosstalk effects is investigated for the adopted CO-OFDM system. A comparison is also made with the benchmark Volterra-NLE to evaluate the impact of stochastic nonlinearities. In Fig. 10, an additional case for exploring the nonlinear phenomena in OFDM is proposed, in which the NLEs under test are performed for each subcarrier. Although this case is unrealistic since it substitutes a separate NLE for each subcarrier, it will provide a holistic and deeper understanding on the physics underlying nonlinear phenomena in CO-OFDM. In Fig. 11, a conceptual diagram is depicted for the application of NLE, and NLE per subcarrier (related to Volterra and N-SVM) on received OFDM signal. N-SVM and Volterra NLEs 'per subcarrier' cases (the dotted lines in Fig. 10) includes 210 NLEs in contrast to the realistic case where 1 NLE process all subcarriers together. In Fig. 10, it is shown that in comparison to the 'per subcarrier'

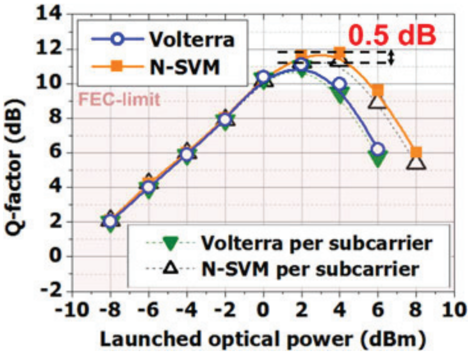

Fig. 10. Q-factor vs. LOP for 16-QAM CO-OFDM equipped with Volterra/N-SVM being processed across all subcarriers and per subcarrier (dotted lines).

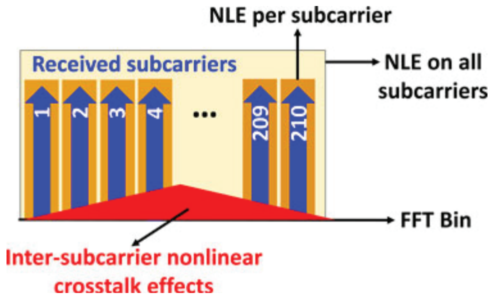

Fig. 11. Conceptual diagram of application of NLE, and NLE per subcarrier (for Volterra and N-SVM) on received OFDM signal.

case, when N-SVM is applied across all subcarriers it reduces the fiber nonlinearity penalty by 0.5 dB. This occurs because when applying N-SVM on each subcarrier separately, ICI nonlinear crosstalk effects are not combated. Finally, it is confirmed that CO-OFDM is influenced by stochastic nonlinearities which cannot be tackled by the deterministic Volterra-NLE.

The results from Fig. 10 indicate that the adopted realistic N-SVM-NLE which accounts for all subcarriers together, provides effective and fast compensation of inter-subcarrier nonlinear crosstalk effects in CO-OFDM.

VI. CONCLUSION

A novel fast N-SVM-NLE of reduced classifier complexity was experimentally demonstrated in 40 Gb/s 16-QAM CO-OFDM at 2000 km of SSMF. In comparison to Volterra-NLE, the proposed N-SVM extended the optimum LOP by 2 dB with very low computational load and execution time. N-SVM tackled inter-subcarrier nonlinear crosstalk effects more effectively than Volterra-NLE especially when applied across all subcarriers simultaneously.

ACKNOWLEDGMENT

The authors would like to thank Dr. S. Le from Nokia-Bell-Labs, Germany and Prof. B. Eggleton from the University of Sydney for their guidance.

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