SVM training based model for nonlinear phase noise mitigation in 16-QAM multicarrier optical system

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We present a training based model namely support vector machine (SVM) to mitigate nonlinear phase noise for 80 Gbps coherent optical orthogonal frequency division multiplexing (CO-OFDM) system. The results revealed that a relatively large nonlinearity tolerance of 16QAM CO-OFDM can be archived with SVM.

Introduction

It is well-known that orthogonal frequency division multiplexing (OFDM) is a special scenario of multi carrier modulation where sub-carriers may be overlapped to others. OFDM has been studied extensively in radio frequency over four decades and optical communication in two recent decades due to some big advantages over single carrier modulation such as the capacity of inter-symbol interference mitigation and high bandwidth usage efficiency [1, 2]. With the rapid development of digital signal processing (DSP), many fiber impairments might be compensated in electrical and digital domains directly. However, one major drawback of OFDM is high peak-to-average power ratio (PAPR). PAPR leads to not only distortion in electrical domain but also in optical domain by nonlinear effects such as self-phase modulation (SPM). Higher launch power is necessary to maintain a required signal-to-noise ratio (SNR) level when multilevel quadractic amplitude modulation (QAM) is employed. As a result, nonlinearity is a severe issue in high speed and long-haul optical OFDM systems. Numerous DSP techniques have been proposed for nonlinearity mitigation in single channel and wavelength division multiplexing (WDM) coherent optical CO-OFDM systems such as PAPR reduction methods [3, 4], digital back propagation (DBP) [5, 6]. In general, the main disadvantages of these techniques are extensive use of fast Fourier transform (FFT) modules, or regular pilots requirements, or prior fiber characteristics to figure out fiber invert impairment functions which sometime is not easy to get. In this paper, we showed the application of a very well-known machine learning, namely support vector machine (SVM) in which no prior information about fiber channel is needed at the receiver for nonlinearity equalization (SVM-NLE) in 80 Gbps 16QAM CO-OFDM system. By numerical validation, the results revealed that SVM-NLE significantly improves the nonlinear tolerance of CO-OFDM.

Support vector machine - brief introduction and its usage for phase noise mitigation in CO-OFDM

Basically, SVM is a classier method. It performs classification problem by constructing hyperplanes in a multidimensional space. By combining multiple two-class SVMs, we can build up a multi-class classifier model to separate multiple class signal. For exam-

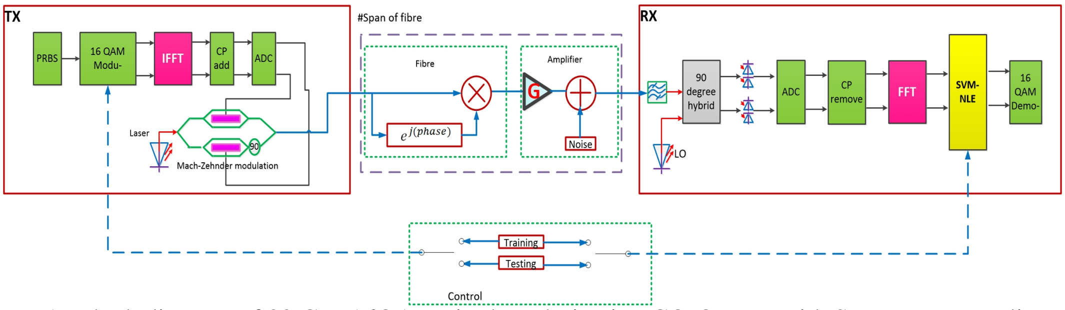


Figure 1: Block diagram of 80 Gps 16QAM single-polarization CO-OFDM with SVM-NLE equalizer

ples, the 16QAM signal is multiple class signal where each cluster belongs to one class. The purpose of SVM is to find the optimal hyperplanes to classify which class the input signal should belong to. Let's take two class classifier for illustration. The hyperplane is obtained through training process from l pairs of training vectors $\{x_i, y_i\}, i = 1, \ldots l$. Each training vector corresponds to a label $Y \in \{1, -1\}$ (two class classification). The training minimizes error function [7]:

$$\min_{w,b,\xi} \left(\frac{1}{2} w^T w + C \sum_{i=1}^{l} \xi_i \right) \tag{1}$$

subjected to constrains $y_i(w^T \Phi(x_i) + b) \geqslant 1 - \xi_i,\ \xi_i \geqslant 0, i = 1, 2, ..l$. Here C is penalty parameter, w is vector of coefficients, b is bias term, and ξ is error which presents non-separable data. The mapping function, $\Phi(.)$, is used to transform input data to the another feature space. Because of practical issue, Kernel trick $K(x_i, x_j) \equiv \Phi(x_i)^T \Phi(x_j)$, is often performed. There are some useful Kernels which were proposed by researchers world-wide such as linear, polynomial, radial basic function (RBF), etc. In our work, we fixed our use on RBF Kernel function: $K(x_i, x_j) \equiv \Phi(x_i)^T \Phi(x_j)$. The whole procedure of SVM consists of two stages: training stage and testing stage. The in-phase (I) and quadrature (Q) of 16QAM signal at receiver form feature vectors for both tranning and testing processes. Each symbol is assigned in one of 16 classes, corresponding to 16 areas in constellation diagram. This class label is also known at receiver, along with nonlinear fiber distorted received symbols. Based on this information, SVM will find the best training model for detector, and the detector uses the model to predict which class the symbols in test process belongs to. To sum up, the following procedure is performed: **(1) Training:** Prepare received complex symbols as (label, in-phase - I, and quadrature - Q), scale I, Q data to [0,1] and choose the RBF Kernel function, use cross-validation to find best C, and use C to train SVM detector. **(2) Testing:** Input testing symbols, compare predict labels (output of SVM detector) to pre-stored transmitted labels to evaluate symbol error rate and bit error rate (BER).

We examined a 16QAM-OFDM coherent optical system as showed in Fig. 1. The long-haul optical link consists of multiple span of 80 km standard single mode fiber (SSMF). Dispersion was ignored since we want to focus on nonlinear phase noise. Erbium-doped fiber amplifiers (EDFA) are used to compensate dispersion and fiber loss. Moreover, each EDFA adds amplified spontaneous emission (ASE) noise which is considered as additive white Gaussian noise process. The complete baseband OFDM signal fed to optical link can be described as [1, 2]:

$$s(t) = \sqrt{P_t} \sum_{i=-\infty}^{+\infty} \sum_{k=-\frac{N_{SC}}{2}+1}^{k=\frac{N_{SC}}{2}} c_{ik} \Pi(t - iT_s) e^{j2\pi f_k (t - iT_s)}. \tag{2}$$

where P_t is launch power, c_{ik} is the i^{th} symbol at k^{th} sub-carrier, N_{sc} is the number of FFT/IFFT and T_s is OFDM symbol period. At the receiver, the optical signal after N_{span} consecutive amplifier stages is detected and converted into electrical domain by a hybrid coherent photodetector. The received signal with nonlinear phase noise, $r(t)$, can be written: [7]

$$r(t) = s(t)e^{j\gamma L_{\text{eff}} N_{\text{span}} \|s(t)\|^2 + j\psi_t + j\theta_t} + w(t). \tag{3}$$

where γ is the nonlinearity parameter of SSMF, $L_{\text{eff}} = (1 - e^{-\alpha L_{SMF}})/\alpha$ is the effective length of SSMF, $\alpha = \alpha_{SMF}$, the sign $\|.\|$ is norm operator. $w(t) \sim \mathcal{N}(0, N_{\text{span}}\sigma^2_{ASE})$. ψ_t is zero mean Gaussian random variable with variance of: $\sigma^2_{\psi} = 2\gamma^2 L^2_{\text{eff}} \|s(t)\|^2 \sigma^2_{ASE}(N_{\text{span}} - 1)N_{\text{span}}(2N_{\text{span}} - 1)/6$. θ_t is a power independent random variable with a mean of $\gamma L_{\text{eff}}\sigma^2_{ASE}(N_{\text{span}} - 1)N_{\text{span}}/2$. Cyclic prefix (CP) is then removed and received signal is converted into frequency domain by FFT function. SVM-NLE block is placed just after FFT to find out the hyperplane for decision.

Simulation model and Results

80 Gbps 16 QAM CO-OFDM system was modeled to evaluate performance of SVM-NLE. An up to 20 spans transmission link in which each span is 80 km long was simulated. Each OFDM symbol has 64 sub-carriers with 12.5 percent overhead of cyclic prefix. Noise figure (NF) of EDFA is 5.5 dB. For SSMF, fiber loss is $\alpha_{SMF} = 0.2\,\text{dB}\,\text{km}^{-1}$, nonlinear Kerr coefficient is $2.6 \times 10^{-20}\,\text{m}^2\,\text{W}^{-1}$. System performance was evaluated by BER which was obtained via error counting and Q-factor. The relationship between Q-factor and BER is $Q(\text{dB}) = 20\log_{10}[\sqrt{2}\text{erfc}^{-1}(2BER)]$. Common threshold before forward error correction (FEC) for 16QAM is 10^{-3}, which translates in Q of 9.8 dB.

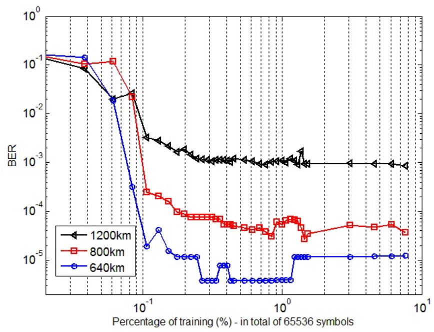
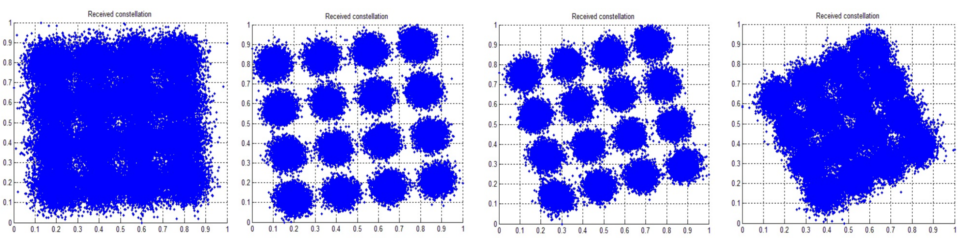


Figure 2: Impact of training

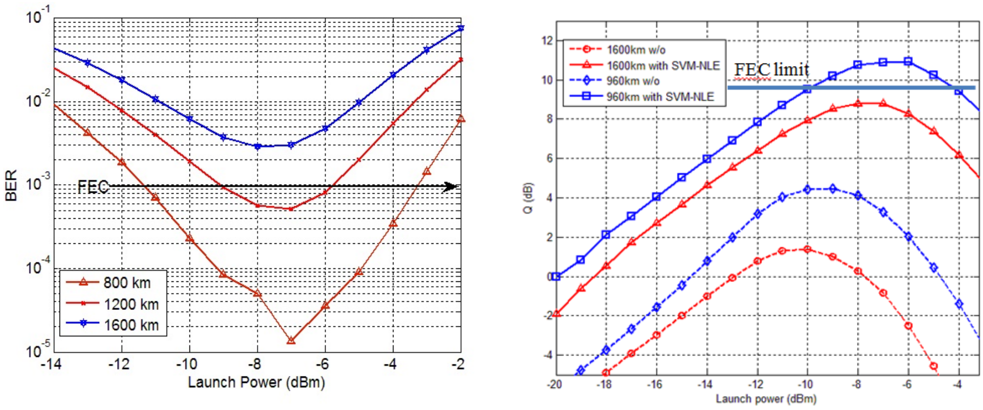
First, the impact of number of training is shown in Fig. 2. As we can see, performance of SVM-NLE will be saturated at around 0.3 percent ($\sim$200 samples) of training. That is why we chose 500 training for all of our simulations afterward.
Fig. 3 illustrates the variation of received constellation after OFDM demodulation according to different launch power for 800 km fiber link. Obviously, noisy constellations will be rotated because of phase factor (nonlinear fiber effect) and Gaussian noise (EDFA). As we can see, there will be an optimum power where SVM-NLE will perform best.

To figure out optimum value of powers, BER versus launch power in different fiber length



(a) -14 dBm (b) -8 dBm (c) -5 dBm (d) -2 dBm

Figure 3: Constellations vs. launch power of 800 km CO-OFDM before SVM-NLE



(a) Performance of SVM-NLE in different level on launch power and fiber length

(b) Comparison of CO-OFDM with and without SVM-NLE

Figure 4: Performance of SVM-NLE in CO-OFDM system with different scenarios

up to 1600 km for 80 Gbps CO-OFDM system with SVM-NLE equalizer was shown in Fig. 4a. It is shown that for each fiber distance, there is an optimum power from -7 dBm to -6 dBm (same as in [8]) where best BER was obtained. The longest distance of fiber can be achieved with SVM-NLE under FEC threshold is just above 1200 km. Lastly, Fig. 4b gives comparison of 960 km and 1600 km CO-OFDM with and without SVM-NLE equalizer. It is clearly shown that SVM-NLE give significant improvement in comparison without equalizer, around 5.5 dB and 9 dB improvement at the launch power of -10 dBm and -6 dBm respectively.

Conclusion

In this paper, we showed an application of machine learning method, SVM-NLE, for nonlinear phase noise mitigation purpose in multi-carrier long-haul coherent optical transmission. The results showed that a remarkable nonlinearitty tolerence was archived with SVM-NLE in CO-OFDM system.

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