Digital Compensation of Signal Distortions in Fiber Communication Lines Based on Perturbation Theory and Machine Learning

P Ya Ilyushin[1], D E Shipilo[1], I A Nikolaeva[1], N A Panov[1], and O G Kosareva[1]

[1]*Faculty of Physics, M.V. Lomonosov Moscow State University, 1 bld.2, Leninskie Gory, 119991, Moscow, Russia. Contact Phone: +7(495)939-16-82*

Contact Email: ilusinpaul@gmail.com

Information transmission throughout long distances requires to use fiber-optical communication lines (FOCLs)as long as their benefits include higher transmission rate, lower absorption [1] and prospects of capacity increase due to implementation of special signal modulations [2] and multiplexing. However, FOCLs are still associated with a number of undesireable effects which include nonlinearity in fiber and built-in elements [3] resulting in distortion of optical signal and corresponding growth of Bit Error Rate (BER). To minimize the influence of nonlinearity onto the accuracy of data transmission [4], a procedure of compensation [5] should be introduced. One of possible ways is to perform compensation digitally after the signal was received at the exit of the FOCL.

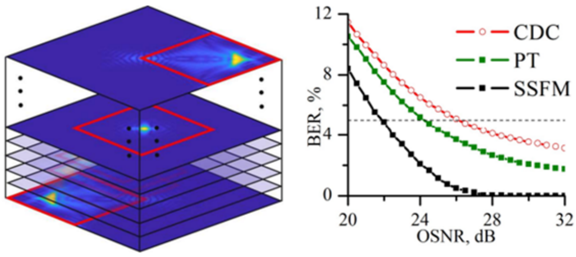

Figure 1: (left) The tensor of convolutional kernel H3(z, t1, t2,t3). The red squares in each section for t3 indicate the part of tensor remaining after the size reduction. Dots indicate the presence of other sections with t3. (right) The compensation quality charecteristic of SSFM, Chromatic Dispersion Compensation (CDC) and investigated Perturbation Theory-based method (PT) for the input signal average power of 9 dBm

In this case, the precise solution of the inverse task of light field propagation can be obtained by integrating the Nonlinear Schroedinger Equation (NSE) over a grid of coordinates by Split-Step Fourier Method (SSFM) [6]. In this work we develop an alternative algorithm of digital compensation based on perturbation theory and machine learning. The approximation of weak nonlinearity allowed us to use a perturbative serial expansion for the optical field, which codes the bit sequence in the FOCL. We derived an expression for the initial sequence of bits through error-containing sequence of bits at the receiver. In the first approximation of perturbation theory the expression contains linear part and triple convolution of optical signal with kernel H3(z, t1, t2, t3). The derived analytical values of H3 tensor components allowed us to reduce the complexity of compensation [Fig. 1(left)].

Machine Learning methods were used to find the components of tensor H3 based on a vast set of randomly generated initial bit sequences, distorted with nonlinearities and stochastic noises in modeled FOCL. The BER in reconstructed bit sequence as a function of the Optical Signal-to-Noise Ratio (OSNR) indicated the quality of compensation. At a fixed magnitude of input signal average power (9 dBm) the characteristic for our proposed method reaches the BER level of 5% at lower values of OSNR than the commonly used CDC algorithm and has a reasonable lag behind the precise solution by SSFM [Fig. 1(right)]. Qualitatively this result is repeated in a wide range of input signal average powers. Thereby, an optimal relation between accuracy and complexity of compensation can be achieved by varying the size of reduced convolutional kernel.

References

[1] M V Arkhipov, A A Shimko, N N Rosanov, I Babushkin and R M Arkhipov, Phys. Rev. A **101**, 013803 (2020)

[2] F Maucher, S Skupin, S A Gardiner and I G Hughes, arXiv:1801.05668 (2018)

[3] P Ya Ilyushin, D E Shipilo, I A Nikolaeva, N A Panov and O G Kosareva, J. Opt. Technol. **91**, 54 (2024)

[4] I Babushkin, U Morgner and A Demircan, J. Phys. A: Math. Theor. **53**, 445307 (2020)

[5] S.V. Gurevich, F. Maucher, J. Javaloyes, arXiv:2306.11359 (2024)

[6] A L Delitsyn, Math. Notes **112**, 199 (2022)