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Dynamic neural network-based methods for compensation of nonlinear effects in multimode communication lines

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Abstract. **We consider neural network-based schemes of digital signal processing. It is shown that the use of a dynamic neural network-based scheme of signal processing ensures an increase in the optical signal transmission quality in comparison with that provided by other methods for nonlinear distortion compensation.**

Keywords: *optical fibre, nonlinear effects, neural networks, mathematical modelling.*

1. Introduction

Nonlinear effects are one of the main factors limiting the capacity of modern fibre-optic communication lines and, therefore, studies in the field of nonlinearity compensation methods in data transmission systems are undoubtedly relevant. Most modern schemes of nonlinear signal processing either simulate backpropagation of optical signals in a fibre line using the split-step algorithm [1] or are based on the use of the Volterra series function approach [2]. However, these methods require large computational costs and can only be used in static data transmission systems, because the parameters of communication lines should be known in advance. Machine learning methods are powerful and effective tools for developing signal processing schemes that can compensate for nonlinear transmission effects. These methods can be used in dynamically changing communication lines and after training require a small amount of computing resources. Despite the fact that in wireless communication systems, signal processing methods based on machine learning have been extensively studied, their application in optical channels has not been properly investigated [3].

In this paper, we study the schemes for nonlinear distortion compensation in multimode trunk lines based on multilayer neural networks. The proposed dynamic neural network-based scheme is compared with the linear compensation scheme and nonlinear compensation technique using digital backpropagation.

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2. Mathematical modelling

The data transmission system in question is schematically shown in Fig. 1. The communication line consists of a transmitter, several spans (100 km each) of multimode fibre with a graded core and a cladding trench [4, 5], erbium-doped fibre amplifiers (EDFAs) and a receiver. For mathematical modelling, the signal propagation lengths from 1500 to 2700 km were investigated, i.e., the number of spans varied from 15 to 27.

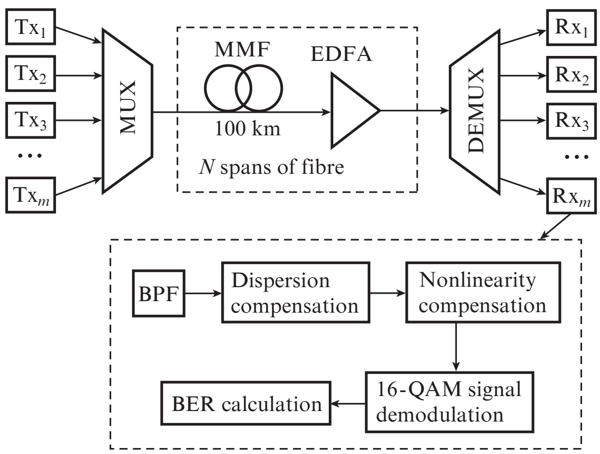

Figure 1. Scheme of the investigated communication line: (Tx_i, Rx_i) transmitter and receiver of signals for the *i*th mode; (MMF) segment of multimode fibre; (MUX) mode multiplexer; (EDFA) erbium-doped fibre amplifier; (DEMUX) mode demultiplexer; (BPF) bandpass filter.

At the transmitter side, 16-level quadrature amplitude modulation signals (16-QAM signals) with a symbol rate R_s = 32 GBaud are generated for each mode. For pulse shaping, use is made of a 'raised-cosine' filter with a roll-off factor of 0.01. The loss in each span is compensated for using EDFAs with a noise figure NF = 4.5 dB.

Nonlinear propagation of optical signals in multimode fibres is described using the Manakov equation in the weak-coupling regime [6], which is solved numerically by the split-step Fourier method. For propagation to be modelled, the following parameters are used: optical fibre loss, α = 0.2 dB km^{-1}; nonlinear fibre parameter, γ = 1.4 W^{-1} km^{-1}; and number of samples per symbol, q = 16.

After transmission over the channel, optical signals are fed to the receiver, in which, after mode demultiplexing, ideal compensation for the group delay and chromatic dispersion is performed. To compensate for the nonlinear distortions, use is made of a linear compensation scheme and backpropagation and neural network-based schemes. The methods considered are compared among themselves by the bit error rate (BER).

3. Dynamic neural network-based scheme for nonlinear effect compensation

The architecture of the proposed neural network is shown in Fig. 2. Complex-valued symbols, received by the receiver after the sample rate is reduced from 16 to 1 sample per symbol interval, are fed to the input of the neural network. In order to take into account the memory effect of the channel in the neural network scheme, use is made of delay blocks (Z^{-1} blocks), which makes the proposed neural network dynamic, i.e., the transmitted symbol X_n is predicted by using not only its corresponding received symbol Y_n, but also several previous ones $Y_{n-1}, Y_{n-2}, \dots, Y_{n-N_{\rm del}}$, where $N_{\rm del}$ is the number of delay blocks. Further input symbols are divided into real (R) and imaginary (I) parts and thus form a feature vector for the neural network.

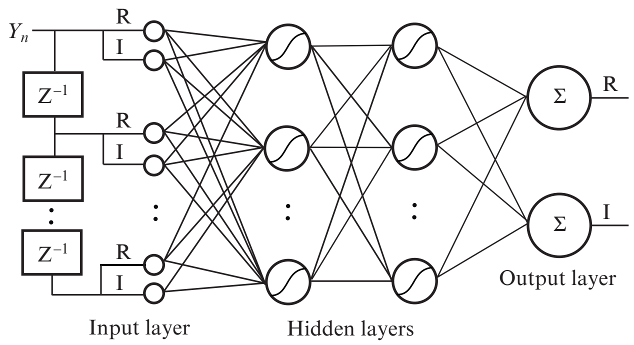

Figure 2. Architecture of a dynamic neural network.

The number of neurons in the input layer of the dynamic neural network under study was $2(N_{\rm del} + 1)$. The network also had two hidden layers of 16 neurons each and an output layer with two neurons corresponding to the real (R) and imaginary (I) parts of the output symbol. For faster training, use was made of the signal backpropagation algorithm proposed by Riedmiller and Braun [7]. The trained neural network recognised the received symbol and predicted the symbol sent from the transmitter. In the experiment we performed 20 runs of 2^{18} symbols each, where 2^{12} symbols were used for training, and the rest were used to calculate the BER.

4. Results of applying the dynamic neural network-based scheme for nonlinear effect compensation

To determine the number of adjacent symbols necessary to account for the channel memory effect, we investigated the dependence of the optimal delay length, i.e., the number of delay blocks used in the network, on the propagation length of the signal (Fig. 3). As is expected, the delay length increases with increasing number of fibre spans used, since in this case

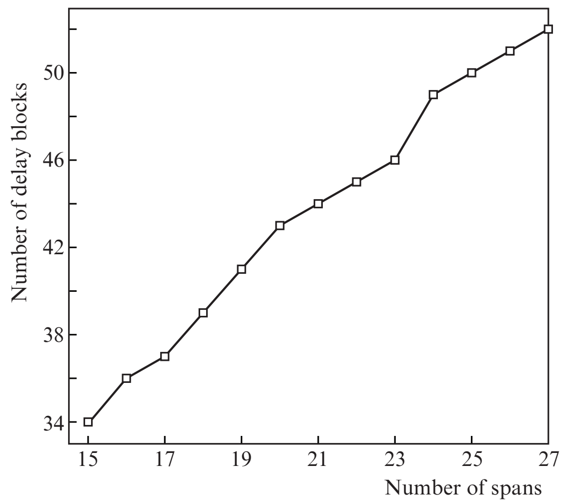

Figure 3. Dependence of the optimal delay length on the number of the fibre spans used.

the memory of the channel also increases, and this dependence is of clearly linear nature.

To study the efficiency of the proposed scheme, it was compared with a linear scheme for nonlinear distortion compensation in which only the phase of the received signal is recovered and with the digital backpropagation method in which the propagation equation is inversely solved using two step digital backpropagation (DBP-2S) algorithm per span.

Figure 4 shows the dependence of BER on the initial signal power for various nonlinear distortion compensation schemes transmitting data over 2000 km. As is expected, a system with a linear compensation scheme shows worse results. The use of a static neural network (i.e., without delay blocks) only slightly improves the data transmission quality compared to the linear scheme, since in this case the channel memory effects are not taken into account. As can be seen from Fig. 4, a dynamic neural network-based scheme gives better results than other nonlinear distortion compensation methods, including the today's most effective DBP-2S method.

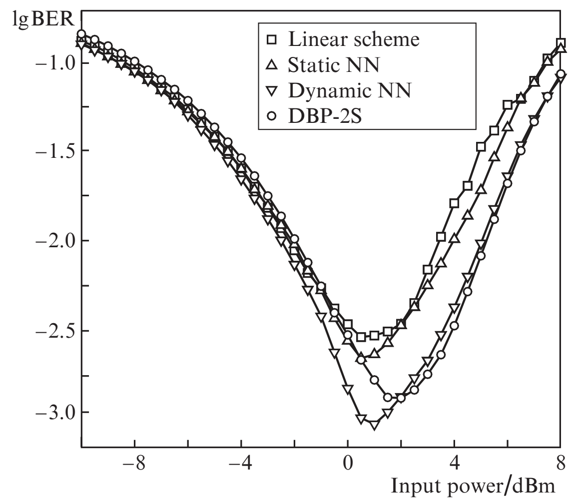

Figure 4. Dependence of the bit error rate on the initial signal power for various nonlinear distortion compensation schemes; NN is a neural network.

Using the obtained curves, we found the optimum power corresponding to the minimum BER for the various number of the spans used. Then, with the obtained power, we constructed the dependence of BER on the propagation length for various nonlinear distortion compensation methods (Fig. 5). In this case, the dynamic neural network-based scheme also surpasses the remaining nonlinear effect compensation methods. Moreover, it allows the propagation length to be increased by 200 km while maintaining the same level of errors compared to the propagation length when using the DBP-2S method.

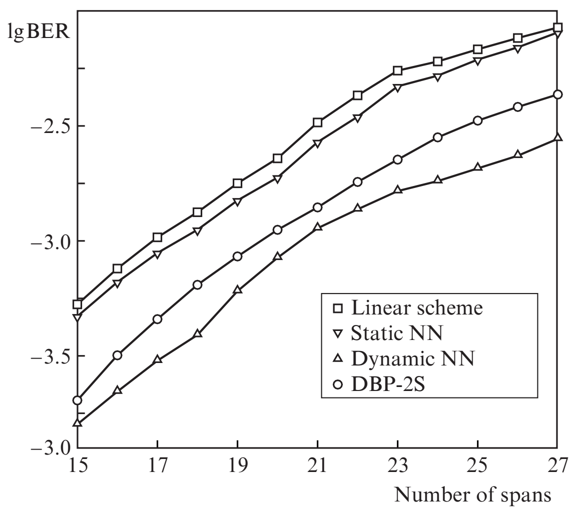

Figure 5. Dependence of the bit error rate on the propagation length for various nonlinear distortion compensation methods.

Thus, we have proposed a dynamic neural network-based scheme for processing optical signals and compensating for nonlinear distortions in a receiver. For this scheme, we have determined the dependence of the delay length on the number of spans of the communication line. We have compared the quality of data transmission for various nonlinearity compensation methods and have shown the superiority of the proposed scheme over the linear compensation scheme and the two-step digital backpropagation method.

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