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Application of combined optical signal processing methods to compensate for nonlinear effects in fibre-optic communication links

A.S. Skidin, O.S. Sidelnikov, M.P. Fedoruk

Abstract. **We report on the use of complex quadrature amplitude signal processing methods based on a combination of static neural networks and special modulation techniques. The conditions are found that allow one to construct the most effective combination of signal processing methods for transmitting signals with considerable power (in the nonlinear regime). Using analytical methods, it is shown how the statistical properties of a signal affect the efficiency of combined processing methods.**

Keywords: *optical fibre, nonlinear effects, neural networks, modulation.*

1. Introduction

One of today's most urgent tasks aimed at increasing the capacity of modern fibre-optic communication lines (FOCLs) is the compensation for nonlinearities [1, 2], which manifest themselves in the form of various effects described quite well in the literature [3]; these effects influence the signal within a single wavelength division multiplexed (WDM) channel, as well as several channels (interchannel interaction). The presence of nonlinear effects imposes a number of restrictions on the total signal power and on the power of its individual components, for example, individual WDM channels. Since the degree of influence of nonlinearities on a signal increases with increasing its power, in recent years several methods have been proposed to limit the signal power while maintaining as large bandwidth as possible [2, 4]. In particular, this is achieved by using modulation formats with probabilistic restrictions on the appearance of given symbols, which correspond to points on the signal constellation with maximum power [4]. However, the disadvantage of these methods is that their use in itself requires a reduction in the nominal bandwidth, which is due to the prohibition (full or partial) of the appearance of certain symbols in the transmitted data. Currently, approaches related to machine learning and neural networks [5] are also being actively used, aimed at improving detection without reducing the nominal bandwidth. Such approaches are a reasonable alternative to the digital back-propagation method; despite the fact that backpropagation methods can theoretically almost completely compensate for distortions, their use in real time now runs into a number of difficulties due to the computational complexity of the backpropagation problem. Under these conditions, methods of machine learning demonstrate quite promising results [6] with a small complexity of their implementation.

In this paper, we consider a combination of two methods used to process an optical signal in a FOCL: constrained modulation and neural networks. A 16 point quadrature amplitude modulation (16-QAM) signal is used as an initial signal, since this modulation format is in a certain sense optimal from the point of view of an increase in the nominal capacity and transmission distance while maintaining an acceptable reception quality [1, 2]. We have shown that the combined use of neural networks and constrained modulation enhances the capabilities of each of the methods; this circumstance is explained from an analytical point of view.

A.S. Skidin, O.S. Sidelnikov, M.P. Fedoruk Novosibirsk State University, ul. Pirogova 2, 630090 Novosibirsk, Russia; Institute of Computational Technologies, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 6, 630090 Novosibirsk, Russia; e-mail: o.s.sidelnikov@gmail.com

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2. Complex optical signal processing

To construct complex signal processing schemes in order to reduce the effect of the Kerr nonlinearity on the signal, it is necessary to take into account the values of the power of the transmitted signal. Consider a signal generated using the 16-QAM modulation format: as was shown in [4], the bit error rate (BER) for such a signal is largely determined by the power distribution of the symbols. The maximum BER is observed with a uniform distribution, while reducing the probability of the appearance of symbols set by the maximum power on the signal constellation leads to a significant decrease in BER (two to five times). Similar approaches to probabilistic constellation shaping modulation (PCS modulation [7]) make it possible to increase the average signal transmission power without degrading transmission quality.

To verify the efficiency of signal processing schemes, we performed numerical simulation. The check was carried out using the signal transfer circuit shown in Fig. 1. In this circuit, the transmitter generates a 16-QAM signal and processes it, if necessary, by a variable-redundancy PCS modulator (i.e., with a variable degree of uneven distribution of symbols in the data stream). The link consists of 10 spans; each span includes a segment of a 100 km long fibre and an amplifier with a noise level of 4.5 dB. The noise caused by the erbium-doped fibre amplifier is added to the optical signal after each amplifier at the end of the span. At the Rx receiver, the optical signal first passes through a band-pass filter (BPF) with a bandwidth BW_{BPF} for noise removal. The receiver compensates for chromatic dispersion and phase shift, and can also use neural networks to better compensate for channel distortion (to compare data transfer efficiencies we did not use it in all cases). In mathematical modelling of signal transmission through an optical fibre, we used the nonlinear Schrödinger equation [3], which describes the evolution of the slowly varying envelope of the optical signal $A(z,t)$:

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2}A - \mathrm{i}\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + \mathrm{i}\gamma|A|^2 A. \quad (1)$$

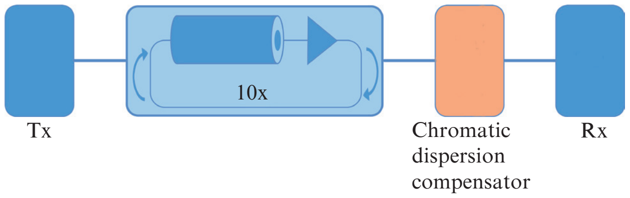

Figure 1. Schematic of the communication link.

This equation was solved numerically using the symmetric split-step Fourier method with the following parameters: an attenuation coefficient, $\alpha = 0.2$ dB km^{-1}; a fibre nonlinearity, $\gamma = 1.4$ W^{-1} km^{-1}; a chromatic dispersion, $\beta_2 = -25$ ps^2 km^{-1}; a wavelength, $\lambda = 1550$ nm; and the number of samples per period, $q = 16$.

Figure 2 shows the signal constellation of the 16-QAM format, divided into rings according to the power of various symbols; near the ordinate axis, the relative error rates for different rings obtained by numerical experiments are shown. It can be seen that the probability of errors in the transmission of symbols from the outer ring is four times the probability of transmission from the inner ring.

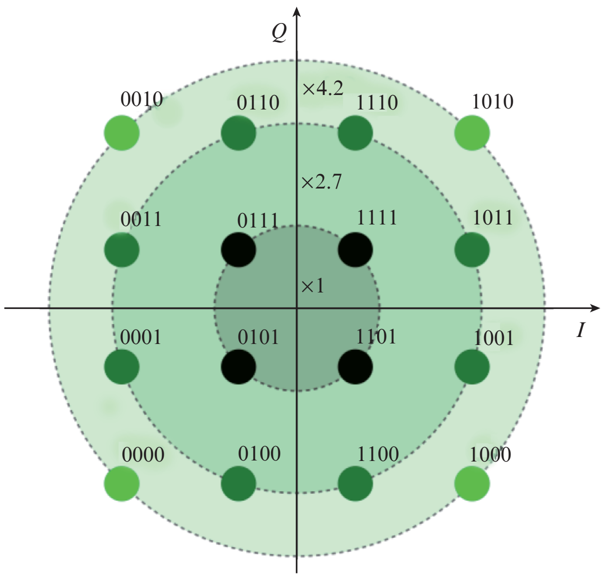

Figure 2. Signal constellation of the modulation format and the relative bit error rates for the constellation rings.

To optimise signal processing, we consider a two-step scheme based on the combined use of PCS modulation and a static neural network, the scheme of which is shown in Fig. 3. This neural network consists of an input layer, two hidden layers and an output layer. The real and imaginary components of the received symbol are fed to the input of the neural network, thereby forming the vector of features of the neural network. Each hidden layer contains 16 neurons; on the output layer, the neural network returns the transformed real and imaginary parts of the symbol. As an activation function, a sigmoid was used on the hidden layers, while a linear transfer function was used on the output layer. Neural network training was performed using Riedmiller's resilient backpropagation algorithm.

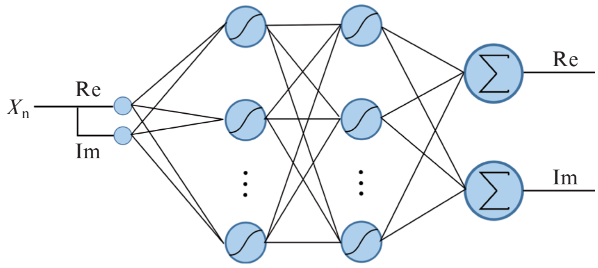

Figure 3. Structure of the neural network used for PCS-modulated signal processing.

In the combined signal processing circuit, the PCS modulation is implemented in two phases: first, the error statistics in symbols is determined by transmitting the standard signal without any restrictions on symbols during modulation; then, the obtained statistics of errors is used to construct an optimal set of probabilities (the optimisation process is described in [4]). To fully use PCS modulation, it is sufficient to find the optimal probabilities of the distribution of symbols in power, taking into account the characteristics of a particular communication line and signal characteristics.

It is worth noting that from the theoretical information point of view, the presence of significant nonlinearities in the optical channel makes this channel a channel with memory, i.e., the quality of transmission of a particular symbol depends in general on what 'neighbours' it has (both in the temporal and frequency domains when considering WDM systems with a large number of frequency components). This, in turn, means that a static neural network itself cannot by definition completely compensate for the effects of nonlinearities. However, when using PCS modulation in conjunction with a neural network, the channel 'memory' length, as will be shown below, decreases, and for this reason, the effect of the joint application of these two independent signal processing methods is enhanced.

3. Optimisation of a combined signal processing circuit

The combined circuit has one independent parameter, i.e., the redundancy R introduced into the signal by PCS modulation. This redundancy can vary widely, but in practice its optimal values do not exceed 10%–15%, since a further increase in R no longer leads to a large increase in signal processing efficiency. The redundancy is due to the fact that not all possible symbols are used equally in the standard 16-QAM format. Figure 4 shows the results of numerical simulation of six different circuits: without use and with the use of a neural network. The dependence of the received error rate (on a logarithmic scale) on the input power is presented for each circuit. It can be seen that the presence of a neural network in the processing circuit does not have a noticeable effect on the quality of data transmission in the case that there is no PCS modulation (its redundancy is $R = 0$). This is a reflection of the fact that in the nonlinear regime the optical channel has memory, and so the static network does not cope with this regime. With the growth of PCS modulation redundancy, an additional effect appears due to the neural network (at R = 5%, the total BER gain is 0.4 dB, of which 0.1 dB is introduced by a neural network; at R = 15%, the total gain is 1.1 dB, of which 0.3 dB is introduced by a neural network), because PCS modulation itself partially compensates for the channel memory, making the distortion more predictable. Since the presence of a neural network in the signal processing circuit does not affect the actual throughput (the neural network does not add redundancy to the signal), an additional effect is achieved without degrading the bandwidth.

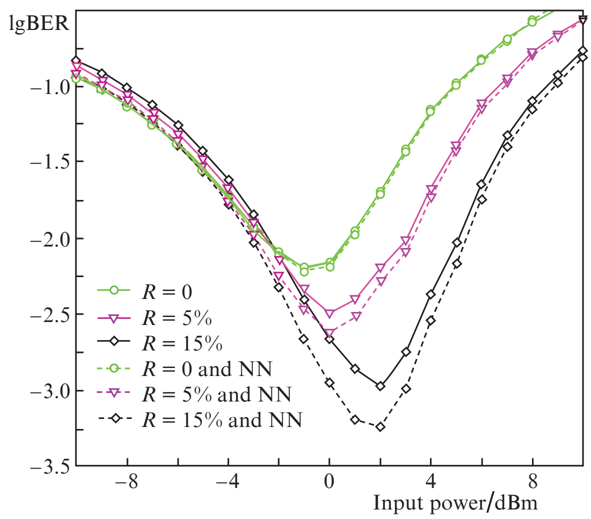

Figure 4. Dependences of BER on the input signal power for various signal processing configurations (NN is the neural network).

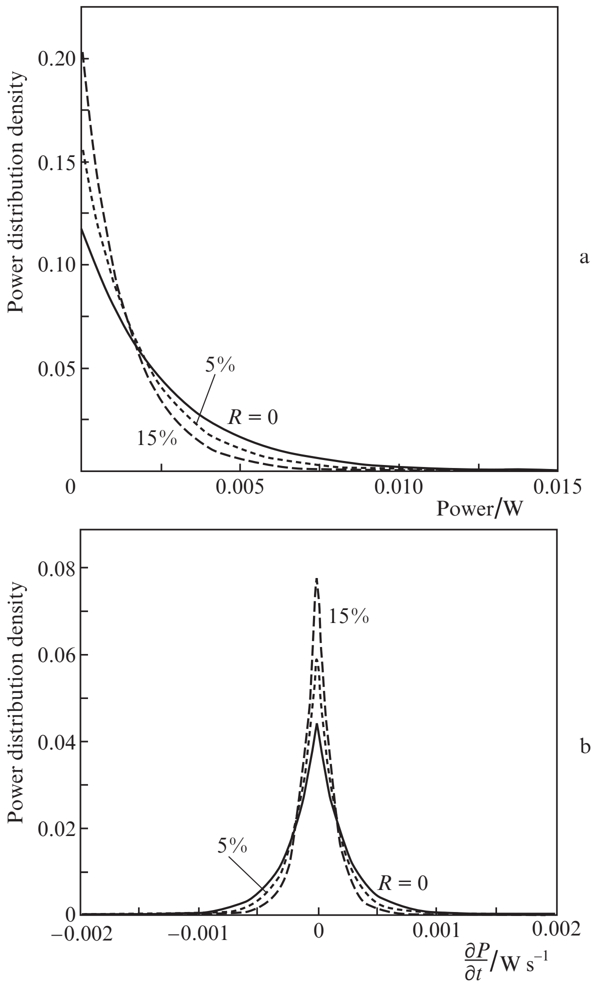

Figure 5. Densities of the distribution of (a) the signal power and (b) its derivative.

It is also worth noting that when use is made of the considered citcuit, the optimal power during optical signal transmission is higher, which is very important because it allows the power to be increased in each of the channels separately (making it possible to transmit a signal in links with a longer span) or the number of channels, thereby increasing average power while maintaining data transmission quality.

4. Theoretical analysis of the results

The combined use of neural networks and special signal modulation produces a greater effect than the separate application of these approaches. This result can be explained both from the point of view of the operation of neural networks and from an analytical point of view. In the first case, an improvement in the operation of a static network in a memory channel is possible when the channel memory ‘decreases’, i.e. the need to adjust the neural network to achieve an optimal result decreases. At the same time, when the transmitted signal is formed using the PCS modulation, the statistics of its characteristics differ from the statistics of the standard 16-QAM format (Fig. 5). Figure 5a shows the power distribution density of various points of the transmitted signal as a function of the redundancy of the PCS modulation, and Fig. 5b shows the distribution density of the derivative of the signal power.

From a mathematical point of view, different statistical properties of the signals lead to a behaviour of distortions that the signal experiences during transmission. To describe these distortions, we transform the Schrödinger equation (1) into a system of equations for the signal amplitude $a(z,t)$ and phase $\rho(z,t)$ [8]:

$$\frac{\partial a}{\partial z} = -\frac{\alpha}{2}a + \frac{\beta_2}{2}\left(2\frac{\partial a}{\partial t}\frac{\partial \rho}{\partial t} + a\frac{\partial^2 \rho}{\partial t^2}\right),$$
$$a\frac{\partial \rho}{\partial z} = -\frac{\beta_2}{2}\left[\frac{\partial^2 a}{\partial t^2} + a\left(\frac{\partial \rho}{\partial t}\right)^2\right] + \gamma a^3. \qquad (2)$$

With the substitution $P(z,t) = a^2(z,t)$, we obtain the system of equations:

$$\frac{\partial P}{\partial z} = -\alpha P + \frac{\beta_2}{2}\left(2\frac{\partial P}{\partial t}\frac{\partial \rho}{\partial t} + 2P\frac{\partial^2 \rho}{\partial t^2}\right),$$
$$\frac{\partial \rho}{\partial z} = -\frac{\beta_2}{2}\left[-\frac{1}{4P^2\sqrt{P}}\left(\frac{\partial P}{\partial t}\right)^2 + \frac{1}{2\sqrt{P}}\frac{\partial^2 P}{\partial t^2} + \left(\frac{\partial \rho}{\partial t}\right)^2\right] + \gamma P. \qquad (3)$$

One can see from Fig. 5 that with increasing redundancy of the PCS modulation, the dispersion of the instantaneous power values decreases as compared to that for the standard 16-QAM modulation. This, in turn, limits the range in which the sum values reside

$$2\frac{\partial P}{\partial t}\frac{\partial \rho}{\partial t}+2P\frac{\partial^2 \rho}{\partial t^2},$$

as well as the range of changes in the value of the expression

Thus, the magnitudes of the terms in system (3) with a dispersion coefficient β_2 are decreased, i.e. the influence of dispersion effects is reduced, while reducing the size of the channel memory. The same behaviour of the terms of the equations takes place in the case when the initial signal power is small, with the only difference that at low power there is a limited range of variation of the terms in the equation for power, and at a high power in the case of PCS modulation – in the equation for phase due to the presence of power in the denominator at a small dispersion of the derivative of power. Consequently, the instantaneous values of the derivatives of amplitude and phase in the spatial variable ($\partial/\partial z$) will also have less dispersion.

Thus, the processing circuit makes it possible to partially level the main factor limiting the transmission of an optical high-power signal, since the continuous interaction between the dispersive and nonlinear effects, which is described in system (3) by the products of phase and amplitude terms, is the main problem in high-power signal transmission. As shown above, the effect of these products in equations (3) is reduced by using the proposed signal processing circuit.

5. Conclusions

We have considered the application of complex quadrature amplitude signal processing methods based on a combination of static neural networks and special modulation techniques. It has been demonstrated and analytically substantiated that the combination of the two approaches to signal processing allows one to achieve a better result than the separate use of these approaches. The results of research show that the application of the proposed approach not only decreases the frequency of bit errors with redundancy $R \leqslant 10\%$ by three or four times, but also increases the optimum value of power, ensuring a minimum error rate at the receiver; this, in turn, makes it possible to more fully utilise the bandwidth of the link.

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