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Comparative analysis of algorithms for compensation of nonlinear distortions in fibre-optic links

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Abstract. **We report the results of numerical modelling and comparative analysis of two algorithms for digital signal processing intended for signal demodulation in fibre-optic links (FOLs) operating in a nonlinear mode. The first algorithm is based on the use of nonlinear Schrödinger filters and the second one utilises the 'reception in general with bit-by-bit decision making' technique. It is found that the latter algorithm is more noiseproof, compared to the first one (with a SNR gain of about 0.5 dB), in single-channel fibre-optic links, and its operation does not require knowledge of the link parameters; therefore, the second algorithm can also be constructed for wavelength-division multiplexing systems.**

Keywords: *fibre-optic link, nonlinear distortions, mathematical modelling, nonlinear Schrödinger filter, algorithm for reception in general with bit-by-bit decision making.*

1. Introduction

In transmitting discrete messages over trunk fibre-optic links (FOLs) with wavelength-division multiplexing (WDM), the power of the transmitted signal increases with increasing number of spectral channels, which causes additional nonlinear distortions, and this, in turn, increases the error probability [1]. In contrast to the case of a linear communication channel, this increase cannot be compensated for by an increase in the transmitted signal power, since the latter will lead to an increase in the level of nonlinear distortions.

In communication lines without dispersion compensation, an even more complicated effect is observed: transmitted signals become overlapped, and the effect of nonlinear interaction decreases. In such systems, the combined action of the Kerr nonlinearity and chromatic dispersion manifests itself as an additional Gaussian noise [2, 3]. In a number of works, the results of experiments are presented that confirm the adequacy of the nonlinear Gaussian noise model [4–8].

To date, there are various approaches to the problem of suppressing nonlinear distortions: forward error correction, use of special modulation formats that are not sensitive to such distortions [9–11], etc.

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In this paper, we consider only two quite simple algorithms for signal processing that can be used to demodulate signals in FOLs in the presence of nonlinear distortions.

2. Nonlinear Schrödinger filters in the problem of compensation for nonlinear and dispersion distortions in a FOL

Burdin and Grigorov [12] considered a relatively new method of joint compensation for nonlinear effects and distortions caused by chromatic dispersion. To this end, they proposed to use so-called nonlinear Schrödinger filters (NLSFs). Their synthesis is based on the known split-step method [13], and the mechanism of joint compensation for various types of distortions relies on the phase nature of nonlinearity in optical fibres and other components of FOLs.

The nonlinear Schrödinger filter is an 'electrical equivalent' of the nonlinear Schrödinger equation (NLSE) [13] and can be used to solve various problems of signal and image processing. To jointly compensate for nonlinear and dispersion distortions at the FOL output of a fibre-optic receiver, it is necessary to use a digital multi-link recovery NLSF (RNLSF) consisting of linear and nonlinear links in series with the following characteristics:

$$G^*(\mathrm{i}\omega) = \exp(\mathrm{i}d\Delta\eta\omega^2) \quad (1)$$

is the traNLSFer function of the linear link;

$$H^*(\Psi) = \exp(-\mathrm{i}\gamma\Delta\eta\,|\,\Psi|^2)\exp(\alpha\Delta\eta) \quad (2)$$

is the coefficient of traNLSFormation of the instantaneous values of the complex envelope $\Psi(\eta, t)$ of the nonlinear link, where η is the normalised spatial coordinate; and d, $\Delta\eta$, α and γ are the parameters of the links. A chain of links with such characteristics is also an 'equivalent' NLSE with conjugate characteristics.

3. Algorithm of reception in general with bit-by-bit decision making in FOLs

Kartashevskii et al. [14] showed that signals in FOLs can be demodulated using the demodulation algorithm that was used earlier in radio channels with dispersion (dispersion) and negligibly small nonlinear distortions, i.e. the algorithm of reception in general with bit-by-bit decision making (RGBDM) [15]. In turn, it is the basis of the system with test pulse and prediction. In such a system, a continuous digital stream of binary signals is divided into information packets with a periodic pause in between; in the centre of the pause there is a test pulse, usually corresponding to a single symbol. This is necessary for the periodic probing of the channel in order to evaluate its impulse respoNLSE. For the demodulation of information packets, the decision-making feedback (DMF) and direct-search RGBDM algorithm, which implements the generalised maximum likelihood criterion, are consistently used [15].

The rule of decision making on the received symbol b_i can be written as follows:

$$\hat{b}_i = \operatorname*{argmin}_j \int_{T_i}^{T_i+MT} [z(t) - \hat{y}_j(t) - \hat{s}_M(t)]^2 \mathrm{d}t, \qquad (3)$$

$$i, j = 1, \ldots, 2^M,$$

where $z(t)$ is the sum of the useful signal and noise; $\hat{y}_j(t)$ is the estimate of the jth realisation of the useful signal against a noise background at the interval $[T_i, T_i + MT]$; T is the clock interval; T_i is current clock interval; $\hat{s}_M(t)$ is a signal characterising the effect of intersymbol interference from signals preceding b_i, and formed using the DMF; and M is the channel memory [15]. For linear types of modulation, the signal $\hat{s}_M(t)$ can be represented in the form

$$\hat{s}_M(t) = \sum_{k=i-M}^{i-1} \hat{b}_k \hat{g}(t - T_k), \qquad (4)$$

where $\hat{g}(t)$ is the channel respoNLSE to the test pulse.

The described system can be used in channels not only with dispersion, but also with relatively fast fading. In this case, the interval between the test pulses is chosen the smaller, the smaller the fading correlation interval.

It was shown in [14] that the described RGBDM algorithm can be used in FOLs operating in an essentially nonlinear mode, despite the fact that the superposition principle is not observed in them.

4. Results of modelling and comparative analysis of the described algorithms

Statistical modelling of the considered algorithms of signal demodulation in FOLs requires large computational resources. Therefore, to compare these algorithms for noise immunity, we calculated numerically the average probability of erroneous reception by the method described in [14], for memory $M = 3$ and relatively small signal-to-noise ratios. Figure 1 shows the obtained dependences for RNLSF and RGBDM algorithms.

5. Conclusions

The following conclusions can be drawn from the obtained modelling results:

1. The RNLSF algorithm is less noise immune than the RGBDM algorithm; however, the loss is relatively small, i.e no more than 1 dB.

2. The advantages of the RNLSF algorithm include the possibility of using the NLSF both in single-channel systems and in WDM systems [16]. Its drawbacks are greater computational complexity, especially for long lines, and the need for an almost exact knowledge of the parameters of the entire link. The first drawback can be partially overcome if the

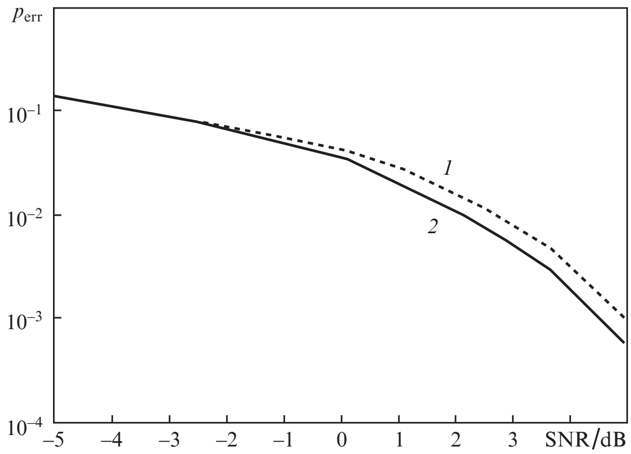

Figure 1. Dependences of the probability of erroneous reception of signals when using (*1*) RNLSF and (*2*) RGBDM algorithms on the signal-to-noise ratio (SNR).

inverse scattering problem is used for the implementation of the NLSF [17], also called the nonlinear Fourier traNLSForm [18–22]. However, in this case, the parameters of all segments of the FOL should be known fairly accurately.

3. The advantage of the RGBDM algorithm is that its work does not require knowledge of any line parameters, and its computational complexity depends little on the FOL length. In addition, the algorithm remains operational if the communication channel is composite, i.e., contains wireless and wired links as well as fibre-optic links. The disadvantage of this demodulation method is that it can be used in pure form only in single-channel systems, where only one optical carrier is used. In WDM systems, this method should be modified, which requires additional investigation.

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