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Study of nonlinearities in the transmission of a QAM signal in fibre-optic communication lines using different carrier pulses

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Abstract. **We study the transmission of a quadrature amplitude modulation signal over a fibre-optic communication line for different carrier pulses forming a signal. It is shown that in using 'raised cosine' and 'root raised cosine' pulses, it is possible to further reduce the bit error rate by an order of magnitude with the help of a special modulation format.**

Keywords: *optical fibre, nonlinear effects, WDM signal, carrier pulses.*

1. Introduction

In considering modern fibre-optic communication lines (FOCLs), the question of how to generate the transmitted signal is important enough, since the magnitude and character of the distortions with which it will be transmitted depend markedly on how the signal will be generated. The dependence of the signal distortion on its character is caused by the influence of nonlinearities on signal propagation [1], which are related to the peculiarities of the physical nature of optical fibres. Of the basic characteristics of signal generation, it is necessary to single out the number of frequency components of the signal (WDM channels) and their distribution over the frequency range, the shape of the carrier pulses and the modulation formats used for data transmission. Separately, it is worth noting the possibility of varying the content of transmitted data, since it, strictly speaking, also affects the quality of the information transfer [2]. Thus, using these characteristics, it is possible to find a signal generation method in order to maximise the use of the line bandwidth on the transmitter side and to optimise signal reception on the receiver side, taking into account specific line characteristics so as to maintain, at the maximum possible data rate, an acceptable reception quality providing (by using error correction algorithms) a level of the bit error rate BER $\approx 10^{-9} - 10^{-12}$.

In this paper we consider the influence of the shape of the carrier pulse on the error statistics [2 – 4], as well as study the potential for reducing distortions using adaptive signal modulation [2, 5, 6], which can be applied in real time for ensuring the optimum data transmission. In transmitting optical signals over fibre-optic communication lines, the 16-QAM (quadrature amplitude modulation) format is used. In the course of the work, analysis of bit and symbol errors in a highly nonlinear mode is performed. The main method of research is mathematical modelling.

2. Mathematical modelling

The data transmission system used in the work is schematically shown in Fig. 1. It consists of ten spans of 100 km each. At the Tx transmitter, 16-QAM signals with a symbol rate R_s (varying from 10 to 100 Gbaud) and different pulse shapes are formed. The noise caused by the EDFA 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 bandpass filter (BPF) with a bandwidth BW_{BPF} to remove noise. After that, the ideal compensation for chromatic dispersion and nonlinear phase shift is realised in the receiver.

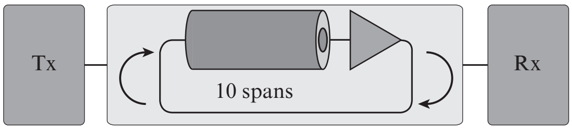

Figure 1. Scheme of the communication line in question.

In the mathematical modelling of signal propagation along an optical fibre, the nonlinear Schrödinger equation (NSE) was used, which describes the evolution of the slowly varying envelope of the optical signal $A(z, t)$:

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2}A - \mathrm{i}\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + \mathrm{i}\sigma|A|^2 A,$$

where α is the optical loss in the fibre (α = 0.2 dB km^{-1}); β_2 is the chromatic dispersion (β_2 = –25 ps^2 km^{-1}); and σ is the nonlinear parameter of the fibre (σ = 1.4 W^{-1} km^{-1}). This equation was solved numerically using the symmetric split-step Fourier method. The following parameters were used for the simulation: the number of samples for the period $q = 16$, the number of symbols $N_s = 2^{18}$, the wavelength λ = 1550 nm and the noise figure of the amplifier NF = 4.5. To obtain statistically reliable results, 100 symbol sequences of 2^{18} symbols in length were transmitted. Thus, the total number of 16-QAM symbols was 2.62×10^7.

For the analysis, we used 'raised cosine' (RC pulse), 'root raised cosine' (RRC pulse), hyperbolic secant (Sech pulse) and also Gaussian (G) and rectangular (Rect) pulses. To

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obtain reliable results, the pulse duration parameter was chosen in such a way that the signals of all used forms had the same half-width of the spectrum. In carrying out numerical experiments for different pulse shapes, the bandwidth $\mathrm{BW}_{\mathrm{BPF}}$ of the bandpass filter plays an important role, which is necessary for optimal detection of the received signal; this value was defined as the ratio $\mathrm{BW}_{\mathrm{BPF}}/R_{\mathrm{s}}$, and for each type of pulse, the bandwidth, at which the minimum bit error rate BER was observed after the signal passed through the line, was separately optimised.

3. Investigation of signal distortions for various pulse shapes

Figure 2 shows the dependence of BER on the initial signal power for pulses of different shapes. As follows from the figure, the signal in the form of an RRC pulse has a minimum value of BER in comparison with pulses of other shapes. Here it is worth noting that, in general, the transmission quality is related to the width of the spectrum occupied by the pulse: thus, a rectangular pulse provides the worst quality of data transmission among all the pulses considered, while occupying a wide spectrum. As for RC and RRC pulses, the roll-off factor was assumed to be equal to 0.2, because preliminary results showed that when the roll-off factor is varied, the dependence of BER on the initial signal power undergoes only minor changes, and therefore in our case this dependence can be neglected.

In addition to the simple effect of the pulse shape on the bit error rate, the distribution of these errors over various discrete states of the 16-QAM format was also investigated [6]. All states are divided by the signal power. The signal constellation of the 16-QAM format has a rectangular shape and all its discrete states are in three concentric circles, corresponding to the powers p (states of lowest power, inner circumference, IC), $5p$ (mean power, middle circumference, MC) and $9p$ (states corresponding to the maximum power, the outer circumference, OC).

The obtained error rate distributions along circumferences with different powers for various types of pulses differ insignificantly. Figure 3 shows the dependence of the symbol error rate (SER) on the symbol rate for the RC pulse. As can be seen from the figure, symbols from the outer circumference, having a larger power, are subjected to large distortions as a result of nonlinear effects compared to symbols of lower power. In this case, the distribution depends on the symbol rate, since with its growth the pulse width and, respectively, the dispersion length decrease, i.e., at larger R_{s} the dispersion acts more strongly on the signal, expanding it and decreasing the intensity at some points, and therefore the nonlinearity will less distort such a signal. This, in turn, causes a uniform distribution of errors in symbols of different power in the case of a large symbol rate.

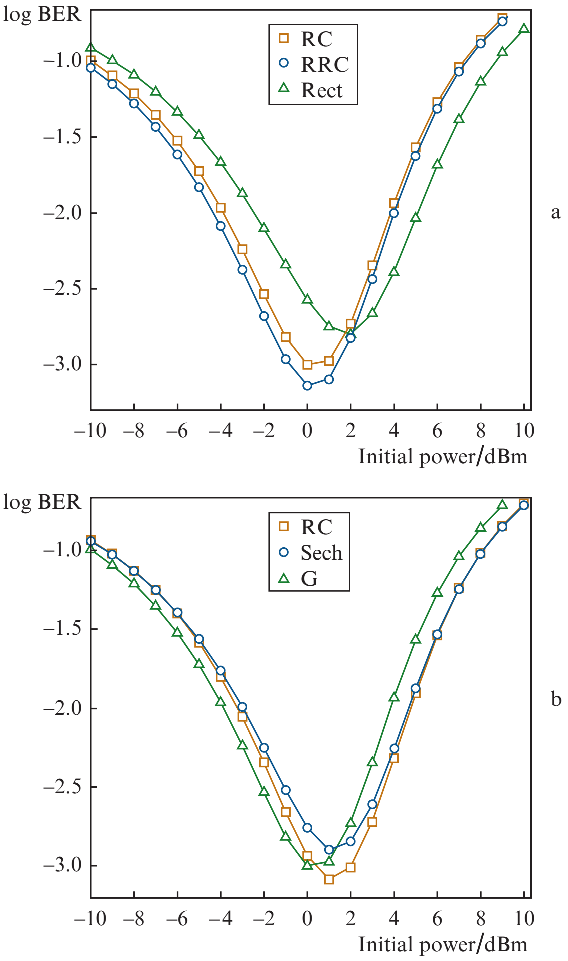

Figure 2. Comparison of the symbol error rates for signals generated using pulses of different shapes.

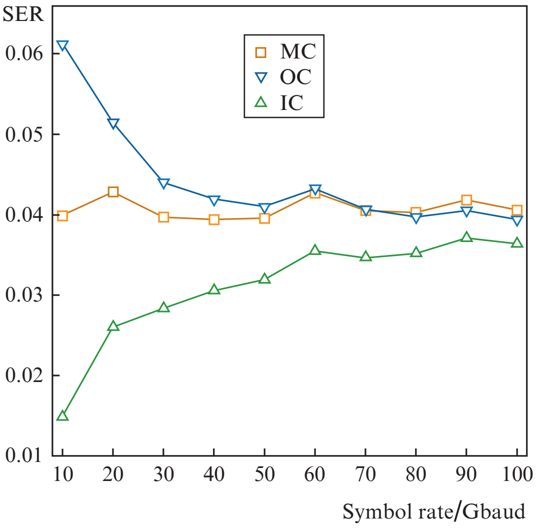

Figure 3. Dependence of the distribution of the symbol error rate with respect to power on the symbol rate for the carrier RC pulses.

4. Use of adaptive modulation for optical signal optimisation

The obtained nonuniform distribution of the symbol error rate with respect to powers allows us to assume that the use of special methods of signal formation [2, 5, 6] can significantly improve the quality of information transmission for different carrier pulses. In order to optimise the transmission quality, the method of adaptive signal generation was applied; in this case, the main types of carrier pulses were investigated as above.

The adaptive modulation method involves reducing the number of allowed states from a common 16-QAM discrete state space. The thus obtained format has on the average a smaller number of states per symbol (less than 16), i.e., the nominal data transmission rate in the channel will be smaller. However, as shown below, due to this limitation, it is possible to reduce significantly the error rate in the absence of any physical changes in the line. The measure of the input constraints is estimated by the parameter R, which is defined as the reduction in the nominal data transmission rate relative to the 16-QAM transmission rate without using special modulation. This value can also be called redundancy (by analogy with the error correction code redundancy), since in terms of discrete data, R corresponds to the fraction of redundant information in the message.

Figure 4a shows the dependence of the reduction of the relative number of symbol errors on the redundancy introduced by the method of adaptive signal formation for pulses of different shapes; here $\gamma = \mathrm{SER}/\mathrm{SER}_0$, where SER and SER_0 are the symbol error rates for the encoded signal and unencoded signal, respectively.

It can be seen that even a small redundancy (~10%) makes it possible to reduce the number of errors by a factor of 10 ($\gamma = 0.1$), which can be decisive for many applications. At the same time, the best indicators of reducing the number of errors are achieved for those pulse shapes that initially showed better characteristics (see Fig. 2). We also should note that pulses based on hyperbolic secant, theoretically able to propagate through the fibre without distortion under certain conditions, in practice give a significantly worse result than RC pulses, which can be explained by the practical complexity of realising the ideal propagation conditions for Sech pulses. The worst values are observed for a rectangular pulse, which is due to the wide spectral region occupied by this type of pulse.

To estimate how effectively the number of errors decreases (in terms of signal power), the dependences of the bit error rate on the input signal power for various adaptive modulation applications have been calculated (shown in Fig. 5 for RC and RRC pulses). It is seen that the greatest decrease in the error rate is shown by RC signals: –1.1 dB when the redundancy of the adaptive code varies from 0% to 15%; similar results were obtained for Gaussian pulses. Taking into account that redundancy is nonlinearly dependent on adaptive modulation, it is possible in real cases to provide redundancy adjustment in accordance with the needs of a particular line.

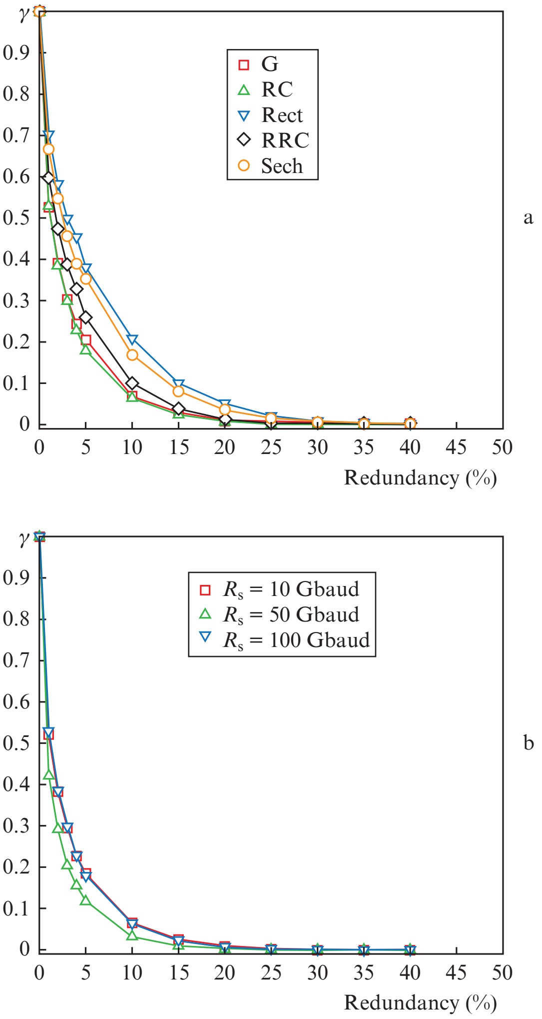

Figure 4. Dependences of γ on redundancy: (a) for different pulse shapes at R_s = 100 Gbaud and (b) at different rates of the RC pulses.

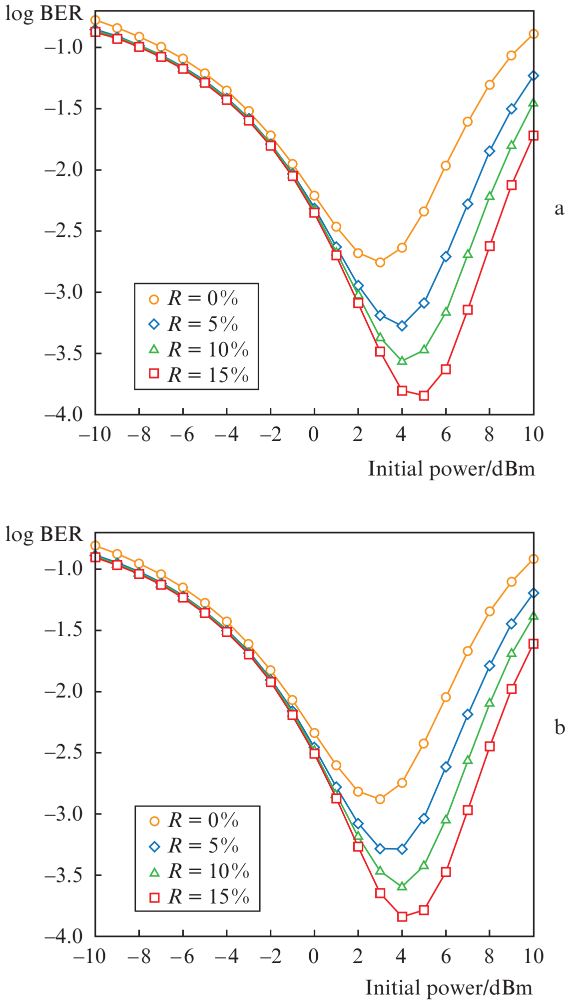

Figure 5. Dependences of the bit error rate on the initial signal power for various redundancy values R of the adaptive modulator for (a) RC pulses and (b) RRC pulses.

5. Conclusions

Thus, we have studied various carrier pulses for operation with a quadrature amplitude signal in high-speed fibre-optic communication lines. The effectiveness of the use of 'raised cosine' and 'root raised cosine' pulses in such lines is shown. Investigations of the joint effect of pulse shape and adaptive modulation on the data transmission quality are carried out. It is found that when adaptive modulation is used, it is possible to flexibly adjust the modulator parameters in order to minimise the error rate. In principle, it is possible to reduce the error rate by 10 times or more with a redundancy of 10% to 15%.

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