

FIBRE-OPTIC COMMUNICATION LINES

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Soliton communication lines based on spectrally efficient modulation formats

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Abstract. **We report the results of mathematical modelling of optical-signal propagation in soliton fibre-optic communication lines (FOCLs) based on spectrally efficient signal modulation formats. We have studied the influence of spontaneous emission noise, nonlinear distortions and FOCL length on the data transmission quality. We have compared the characteristics of a received optical signal for soliton and conventional dispersion compensating FOCLs. It is shown that in the presence of strong nonlinearity long-haul soliton FOCLs provide a higher data transmission performance, as well as allow higher order modulation formats to be used as compared to conventional communication lines. In the context of a coherent data transmission, soliton FOCLs allow the use of phase modulation with many levels, thereby increasing the spectral efficiency of the communication line.**

Keywords: *soliton communication lines, coherent detection, multilevel modulation formats, mathematical modelling.*

1. Introduction

Currently, the main objectives in the development of fibre-optic communication lines (FOCLs) are an increase in the transmission capacity and distance [1]. The vast majority of modern FOCLs are designed in such a way that linear and nonlinear effects of the optical fibre on the optical signal are compensated for during the signal propagation in the link or after its detection at the receiver. If a number of widely used practices (erbium fibre amplifiers and dispersion compensators) already exist to compensate for optical loss and dispersion effects, there are no yet universal methods for compensating or suppressing nonlinear effects and related technologies are at the stage of active research [2–6]. The influence of nonlinear signal distortions on the data transmission quality becomes significant with an increase in the channel rate and a decrease in the distance between adjacent spectral channels and is the major factor limiting a further increase in the bandwidth of conventional links utilising the simplest modulation formats. Hereinafter, the term ‘a conventional link’ refers to a communication link using any kind of dispersion compensation (DCF fibre, dispersion compensation at the receiver) regardless of the shape of the signal envelope.

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The optical-signal power is one of the critical parameters in determining the maximum length of a communication link. When the signal power is low, nonlinearity makes a small contribution to its distortion, but the noise accumulated during propagation from amplifiers can significantly distort the signal. On the other hand, when the signal power is high, nonlinear effects start playing a major role in signal distortion. The signal power is associated with one of the most important FOCL parameters, i.e., a signal-to-noise ratio (SNR). The feasibility of FOCL operation in the region of high SNR values improves the quality of signal decoding and allows the data to be transmitted over longer distances. In addition, we know from Shannon’s theory of quasi-linear signal transmission that in the region of high SNR values a further increase in the spectral FOCL efficiency is possible. Modern communication lines ensuring a high (40–100 Gb s^{-1}) channel data transmission rate operate, however, in the region SNR < 30 dB [7–9], or over short distances [10]. One of the goals of the present work is to investigate a long-haul FOCL operating in the region of high SNRs at high signal powers, i.e., when the nonlinearity effect is the largest. In this context, it is impossible to represent the nonlinear Kerr effect as a nonlinear noise [7]. Thus, we consider a FOCL with a lower channel rate (up to 10 Gbit s^{-1}), but with a greater influence of nonlinear effects on the transmitted signal. Such communication links are typical of long-haul data transmission.

One way to increase the length of the link, while maintaining high spectral efficiency of data transmission, is to make use of soliton FOCLs. A special shape of a soliton pulse maintains a continuous balance of the dispersion and nonlinearity effects. Because of their mutual compensation the soliton preserves its shape as it propagates along the fibre. It is known that at a fixed channel rate, a FOCL with a signal having a Nyquist pulse shape [11] has the highest spectral efficiency, because this pulse shape ensures a dense packing of frequency channels. However, the compensation for the influence of nonlinear effects on the shape of solitons as they propagate over long distances will preserve the high value of such a measure as the product of the spectral efficiency by the transmission distance. This fact makes soliton communication lines more advantageous over conventional data transmission communication links and encourages a further study of the soliton properties [1, 12].

We propose to consider soliton FOCLs in a new context of coherent data transmission, i.e., when an optical phase is used to encode information. Thus, the use of M different phases of a soliton pulse for encoding increases the bit rate by $\log_2 M$ times compared with the standard On-Off Keying (OOK) format, which allows the data transmission rate to be increased at the same value of the bit interval. This approach is an alternative to the standard quasi-linear approach to data transmission in which the nonlinearity and dispersion are compensated for separately. Using multi-level modulation formats together with soliton data transmission will overcome current nonlinear limitations on spectral efficiency of conventional FOCLs [11, 13]. Therefore, the study of data transmission through a fibre optic link by using a train of solitons and spectrally efficient modulation formats is urgent and requires the application of mathematical modelling methods.

This paper deals with mathematical modelling of transmission of optical pulses through a FOCL utilising spectrally efficient signal modulation formats. We present a model of a communication line with an ideally distributed Raman amplification (IDRA) scheme, based on the generalised nonlinear Schrödinger equation. The propagation of an optical signal to a distance up to 5000 km is calculated numerically for both conventional and soliton FOCLs. The results obtained are compared and analysed.

The aim of this paper is to demonstrate the possibility of applying soliton communications links with a multi-level phase encoding to transmit data at a high power of light launched into the fibre and under a significant influence of nonlinearity, where the use of conventional links is complicated.

2. Mathematical model

The object of research is long-haul IDRA FOCLs up to 5000 km in length. For numerical calculations we used a model with ideal distributed Raman amplification, when the optical losses are continuously compensated for so that the average value of the signal power remains constant throughout the fibre length. To describe the propagation of an electromagnetic field along the optical fibre we used a generalised nonlinear Schrödinger equation (NSE) [11, 14]:

$$\frac{\partial A}{\partial z} = -\mathrm{i}\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + \mathrm{i}\gamma|A|^2 A + \mathrm{i}N(z,t),$$

where $A(z,t)$ is the complex envelope of the field amplitude; t is the time; z is the distance along the fibre; β_2 is the chromatic dispersion parameter; and γ is the nonlinearity parameter. Term of the equation, $N(z,t)$, describes the generation of noise arising due to optically amplified spontaneous emission [15]. As a model of noise we use a model of additive white Gaussian noise with spectral density per polarisation (noise power per unit frequency): $N_{\mathrm{ASE}} = n_{\mathrm{sp}}\hbar\omega\alpha L$, where $\hbar$ is Planck's constant; ω is the signal carrier frequency; α is the loss; L is the propagation distance; $n_{\mathrm{sp}} = N_2/(N_2 - N_1)$ is the coefficient of spontaneous emission; N_1 is the number of atoms in the ground state; and N_2 is the number of excited atoms. Numerical simulation was carried out by using the split-step Fourier method for physical processes (symmetric second order approximation scheme) [14]. Values of all the parameters used in the calculations are presented below.

n_{sp}	1.0
$\omega(2\pi)^{-1}$/THz	193.6
α/km^{-1}	0.046
L/km	500–5000
Number of frequency channels	15
β_2/ps^2 km^{-1}	−21.5
γ/mW^{-1} km^{-1}	1.27×10^{-3}

The receiver ensured the compensation of accumulated chromatic dispersion and nonlinear effects by using the back-propagation of the signal. To this end, we used the NSE with opposite signs of the terms and in the absence of the noise term in the equation:

$$\frac{\partial A}{\partial z} = \mathrm{i}\frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} - \mathrm{i}\gamma|A|^2 A.$$

As an initial amplitude, we used the signal amplitude at the receiver. This method of digital signal processing has proven itself in many problems of optics [16–19] and is currently one of the most promising modern methods for improving the quality of signal transmission [20]. For soliton FOCLs this method allows one to reduce inter-channel interaction and interaction of neighbouring pulses with each other.

The transmission quality of pulses was estimated in the calculations by using the error vector magnitude (EVM) parameter [21], which characterises the deviation of the received signal from the initial one due to its distortion. For a train of pulses the EVM is calculated as follows:

$$\mathrm{EVM} = \left[\frac{\sum_i |\boldsymbol{r}_i^0 - \boldsymbol{r}_i|^2}{\sum_i |\boldsymbol{r}_i^0|^2}\right]^{1/2},$$

where $\boldsymbol{r}_i^0$ is the initial state on a complex plane of the constellation diagram and $\boldsymbol{r}_i$ is the amplitude of the received signal. Obviously, the EVM is a measure of the signal deviation from the initial position on the constellation diagram, and, moreover, allows one to estimate the order of the phase modulation format that can be used in fibre optic signal transmission. Thus, for example, at EVM < 25% 8-PSK modulation can be used, whereas at EVM < 55% binary PSK (BPSK) modulation can be applied. To each value of the EVM parameter, there corresponds a uniquely determined bit error rate (BER) parameter [21] for each signal modulation format. All the EVM values used for assessing the choice of the modulation format correspond to BER = 5×10^{-2}.

In numerical calculations we used a pseudo-random sequence of length 2^{14} bits. As a modulation format we selected a quadrature phase shift keying (QPSK) modulation format. In modelling conventional communication links we used pulses with a profile of a sinc function:

$$A(0,t) = \sqrt{P_0}\sin\left(\frac{2\pi t}{T_{\mathrm{b}}}\right)\Big/\left(\frac{2\pi t}{T_{\mathrm{b}}}\right),$$

where P_0 is the initial peak power, and T_{b} is the bit interval. Such a pulse shape has a number of advantages. First, the pulse spectrum has a rectangular shape, which substantially eliminates interchannel interactions. Second, this pulse shape can completely eliminate intersymbol interactions [11, 22]. The selected modulation format allows a comparison of the characteristics of soliton FOCLs with the maximum attainable parameters of conventional FOCLs, such as bit rate, transmission distance and spectral efficiency.

In modelling soliton communication links we used pulses with a profile

$$A(0,t) = \frac{2\sqrt{P_0}}{\exp(-\tau) + \exp(\tau)}, \quad P_0 = |\beta_2|/\gamma T_0^2, \tag{1}$$

where T_0 is the pulse width, and $\tau = t/T_0$. A distinctive feature of a soliton pulse is the relationship between the peak power and the pulse width, as well as 'particle-like' behaviour, such as the elastic interaction. Dispersion and nonlinear effects of the fibre only affect the phase of the soliton, and if we consider these effects independently, it is easy to derive expressions of the dispersion $\mathrm{d}\Phi_{\mathrm{D}}$ and nonlinear $\mathrm{d}\Phi_{\mathrm{NL}}$ phase shifts [23]:

$$\mathrm{d}\Phi_{\mathrm{NL}} = \mathrm{sech}^2(t/\tau)\mathrm{d}z, \;\; \mathrm{d}\Phi_{\mathrm{D}} = [0.5 - \mathrm{sech}^2(t/\tau)]\mathrm{d}z.$$

The sum of these differentials is equal to a constant, and hence, after integration of the Schrödinger equation the initial pulse acquires a phase shift equal to $z/2$, which forms the basis of the mechanism of mutual compensation of dispersion and nonlinear effects.

An important parameter in the design of fibre optic links is the SNR, which is defined as follows:

$$\mathrm{SNR} = 2\frac{B_{\mathrm{ref}}}{R_{\mathrm{s}}}\mathrm{OSNR} = 2\frac{B_{\mathrm{ref}}}{R_{\mathrm{s}}}\frac{P_{\mathrm{ave}}}{P_{\mathrm{N}}},$$

where B_{ref} is the characteristic bandwidth (12.5 GHz); P_{ave} is the average signal power; R_{s} is the symbol data transmission rate; and P_{N} is the noise power [24].

3. Numerical experiment

We have analysed and compared the results of mathematical modelling of soliton and conventional FOCLs, the schematic of which is shown in Fig. 1. The values of the peak power of the initial signal, P_0, are −2, −4 and −6 dBm. This power range covers a region of large SNRs, at which the influence of nonlinear effects is significant and where the comparison is of the greatest interest.

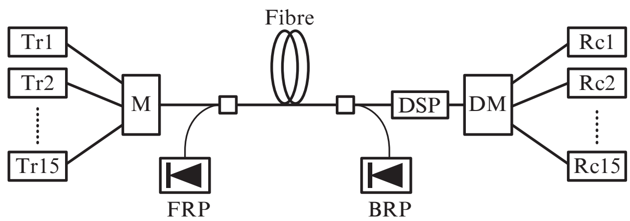

Figure 1. Scheme of a modelled link: (Tr) transponders; (M) multiplexer; (DM) demultiplexer; (Rc) receivers; (DSP) digital signal processing module; (FRP, BRP) laser diodes for forward and backward Raman pump.

For each power P_0 the soliton pulse duration is uniquely determined by (1) and is 164, 208 and 260 ps, respectively. In order to avoid the influence of adjacent pulses on each other, the length of the bit interval must satisfy the relation $T_{\mathrm{b}}/T_{\mathrm{FWHM}} > 2$ [21], where T_{FWHM} is the pulse full width at half maximum. On this basis, we fixed the value of the bit interval T_{b} = 1000 ps, which corresponds to the symbol rate of 1 GBaud. Given the QPSK modulation format, the bit rate was 2 Gbit s^{-1} in one spectral channel for the spectral efficiency of ~ 0.6 bit s^{-1} Hz^{-1}. For adequate comparison of the simulation results the symbol rate for conventional FOCLs was also chosen equal to 1 GBaud.

4. Results

Figure 2 shows the dependence of the EVM parameter on the propagation distance, calculated numerically for the selected peak pulse powers. It can be seen that the value of the EVM parameter increases with the fibre-optic line length, which is due to the signal distortion as a result of simultaneous accumulation of spontaneous emission noise and influence of nonlinear and dispersive effects. The figure also shows that with increasing pulse power in the case of conventional data transmission (Fig. 2b), the EVM parameter increases rapidly, which is caused primarily by the growing influence of nonlinearity when the signal propagates along the fibre. The impact of nonlinear effects can be most conveniently assessed by the nonlinear length parameter

$$L_{\mathrm{NL}} = (\gamma P_0)^{-1}.$$

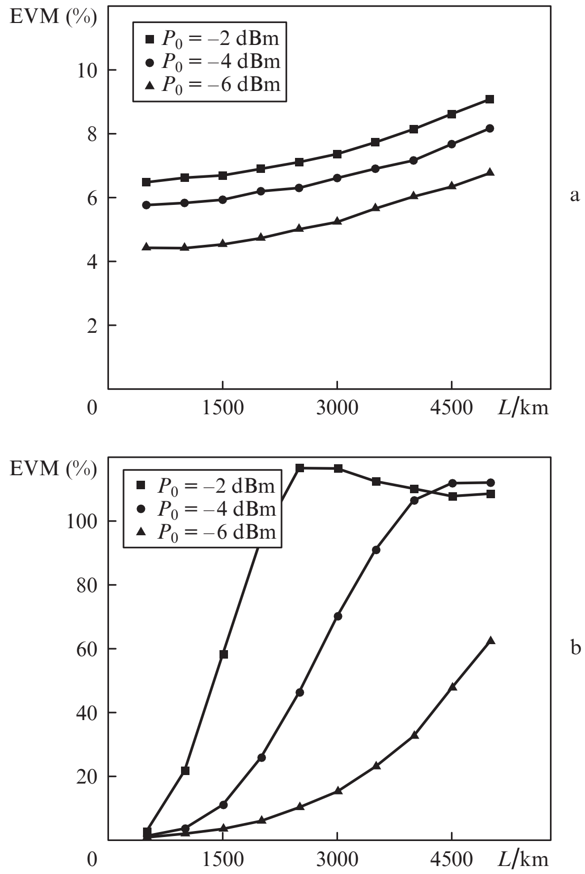

Figure 2. Dependences of the EVM parameter on the propagation distance for (a) soliton and (b) conventional links.

Thus, for example, for a power P_0 = −6 dBm the nonlinear length L_{NL} is 3200 km, and at P_0 = −2 dBm L_{NL} = 1300 km. Therefore, in conventional communication links, when the SNR is large (more than 40 dB), the signal can be transmitted error-free to a distance of more than 1500 km. The maximum transmission distance of a conventional link in this case is reached at the lowest (−6 dBm) power P_0 and is equal to ~4500 km.

Soliton communication links (Fig. 2a), on the contrary, demonstrate a higher stability to a L_{NL} reduction. The EVM values here do not exceed 9%, which indicates good signal quality and the possibility of error-free decoding. The discrepancy between the curves in Fig. 2a is small, because dispersion and nonlinear effects mutually compensate for each other and the latter almost do not contribute to the destruction of the signal. Here, an EVM increase with increasing power P_0 is related to an increase in the intersoliton interaction [25], and the signal transmission distance, at which error-free decoding is possible, does not reach its maximum, i.e., can be longer than 5000 km.

Figure 3 illustrates the signal distortion with increasing propagation distance for soliton and conventional FOCLs. As can be seen, the soliton signal transmission not only has the best transmission quality, but also allows a higher order phase modulation, such as 8-PSK, to be used.

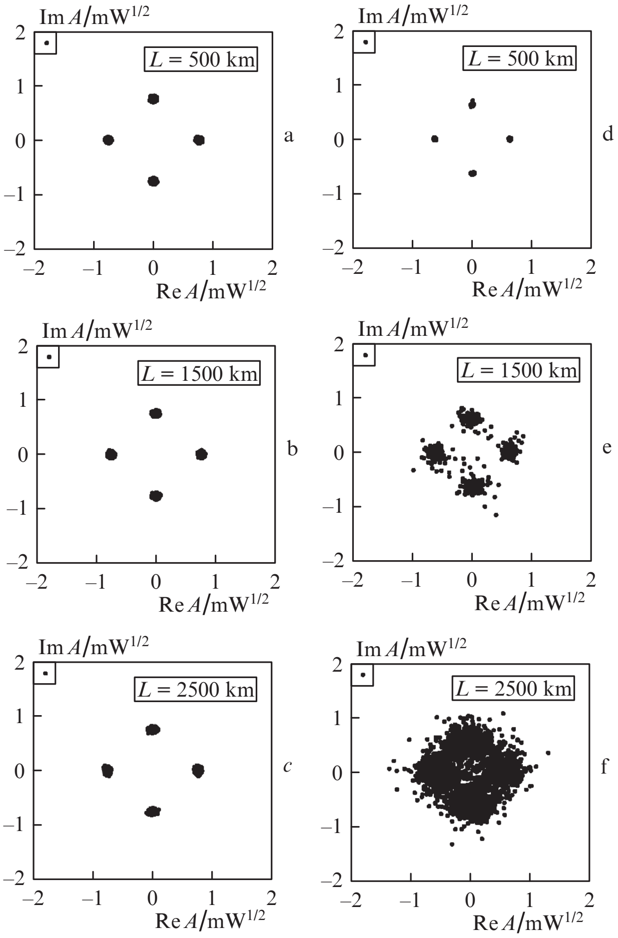

Figure 3. Constellation diagrams for (a–c) soliton and (d–f) conventional FOCLs of different lengths; $P_0 = -4$ dBm, L_{NL} = 2000 km.

Figure 4 shows the diagrams of the received signal after its transmission along a 5000-km soliton FOCL using the 8-PSK format at $P_0 = -4$ dBm. By increasing the modulation order, the bit rate increased to 3 Gb s^{-1} in a single channel at a spectral efficiency on the order of 1 bit s^{-1} Hz^{-1}. The EVM value in this case is increased less than twice as compared to the case of QPSK modulation and is still below the threshold value (less than 25%) for error-free detection.

Separately we have studied the influence of accumulated noise on the signal transmission quality. First of all, it must be emphasised that while the peak powers of soliton pulses and sinc pulses were chosen equal, the average pulse powers differed. Nevertheless, for the peak power $P_0 = -6$ dBm, due to the ratio of the pulse width and bit interval, the average powers prove to be of the same order of magnitude and their comparison is justified. Moreover, in order to exclude the contribution of nonlinear effects in the destruction of the signal we will perform the comparison at distances $L < L_{NL}$. Recall that L_{NL} = 3200 km for the power $P_0 = -6$ dBm.

Figure 5 demonstrated the growth of errors with the accumulation of noise. At small (L < 1000 km) propagation distances, i.e., for large SNRs (44–47 dB), the EVM values for both links are the same. Further, as the accumulation of noise proceeds (L = 3000 km, SNR ≈ 42 dB), the EVM value for conventional FOCLs is about five times greater than for soliton FOCLs. This indicates the stability of soliton to the tim-

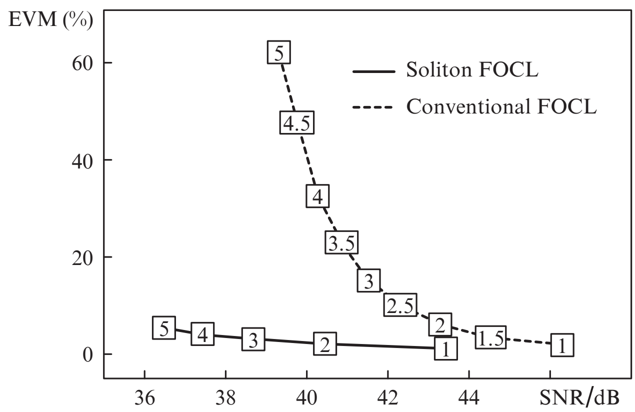

Figure 5. EVM parameter of soliton and conventional FOCLs as a function of accumulated noise. Digits on the curves correspond to the propagation distance (in thousand km).

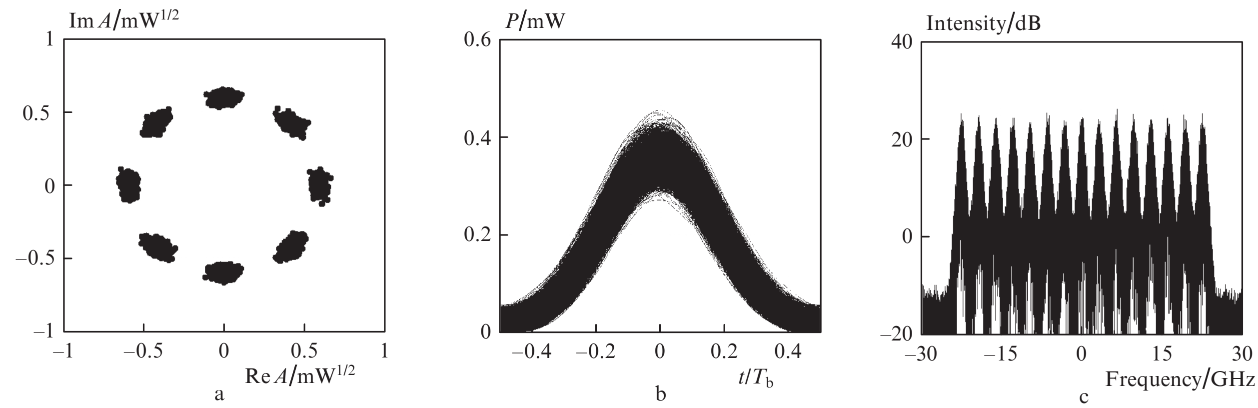

Figure 4. (a) Constellation and (b) test diagrams, as well as (c) spectrum of a signal transmitted through a 5000-km soliton link.

ing jitter caused by the action of accumulated noise on the signal.

5. Soliton communication lines with the channel rate of 10 Gbit s^{-1}

A further increase in the channel rate of soliton communication lines is caused by a decrease in the soliton pulse width, and hence by an increase in the power of the transmitted signal. Let us compare soliton and conventional links transmitting data at a rate of 10 Gbit s^{-1} in a single spectral channel. To exclude a sharp increase in the power, we make use of such signal modulations as 4-ASK/QPSK, 4-ASK/8-PSK and 4-ASK/16-PSK with relevant bit intervals of 400, 500 and 600 ps.

Figure 6 shows the numerically calculated dependence of the EVM on the propagation distance of a soliton link. An increase in the signal distortion with increasing pulse power is explained by an enhancement of the interaction of soliton pulses. It is seen that the data transmission via long-haul FOCLs ($L \leqslant 5000$ km) using many phase-shift keying and several amplitude-shift keying modulation formats (4-ASK/16-PSK) is possible. A similar calculation for conventional FOCLs is presented in Fig. 7. One can see that using a power of 0 dBm and higher, the signal can be transmitted to a distance of no more than 2500 km.

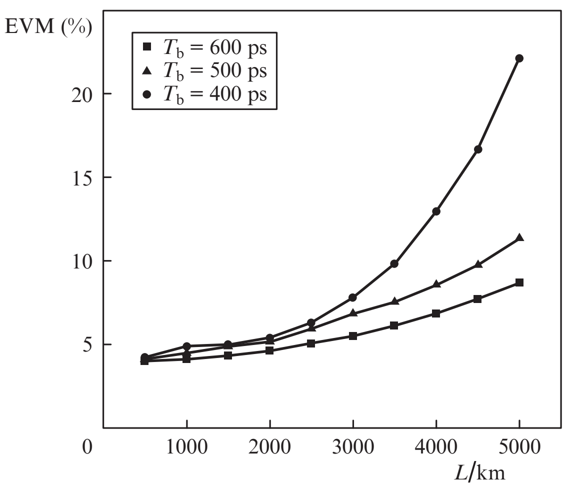

Figure 6. Dependence of the accumulated EVM on the propagation distance for a soliton FOCL with a 4-ASK/16-PSK modulation format.

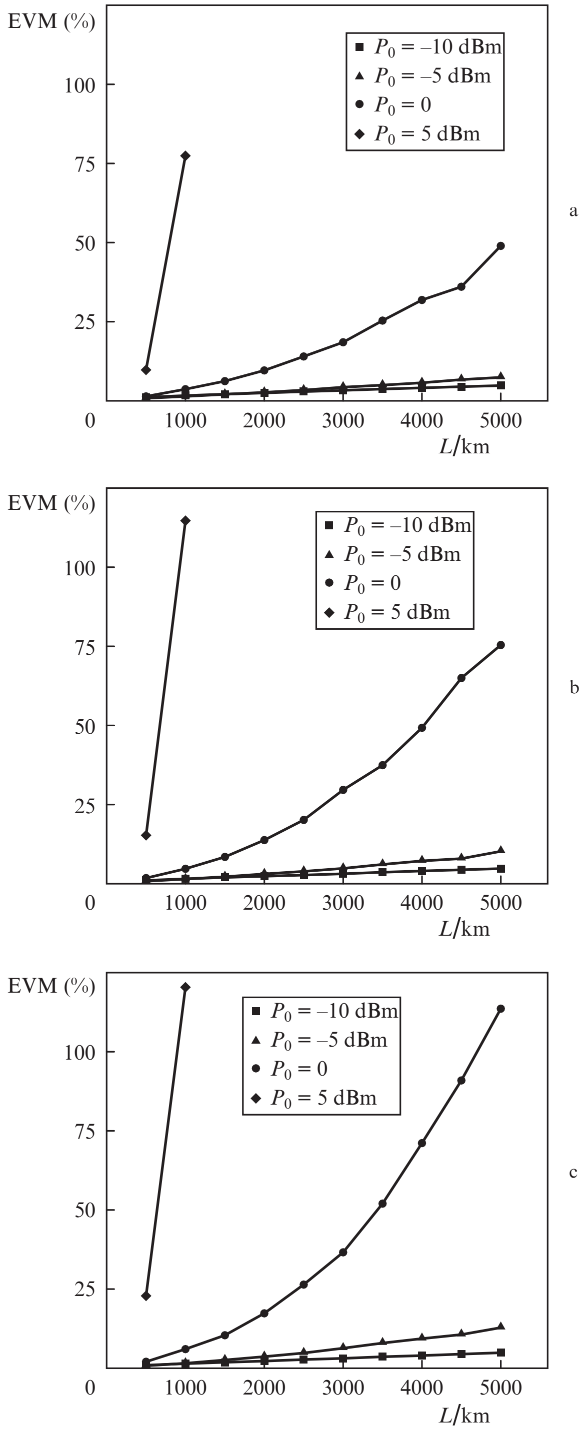

Figure 7. Dependence of the EVM parameter on the signal propagation distance through conventional communication lines at T_b = (a) 400 and (b) 500 and (c) 600 ps.

6. Conclusions

We have mathematically modelled the transmission of optical pulses over soliton and conventional FOCLs by using spectrally efficient signal modulation formats. It is found that the soliton communication lines are more resistant to the influence of nonlinear effects at a high power of light launched into the fibre, as compared to conventional fibre-optic links. For 5000-km soliton communication lines the SNR, at which correct detection of the received signal is possible, reaches 39 dB.

We have shown that when the propagation distance L is shorter than the nonlinear length L_{NL}, soliton communication lines have a higher stability with respect to accumulation of noise as the optical pulse propagates in the fibre.

Furthermore, we have found that the data transmission rate in one spectral channel over soliton communication lines can be increased significantly with the help of high-order amplitude/phase shift keying phase modulation formats. The spectral efficiency achieved during 10 Gbit s^{-1} data transmission in one spectral channel is 2.4 bit s^{-1} Hz^{-1}.

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