Pulse Shape Influence on Optical System Performance in the Presence of Interference, Dispersive and Nonlinear Effects

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***Abstract* - Dispersion and nonlinear effects are most important limiting factors in optical transmission systems. The research subject of this paper is the common influence of dispersive and nonlinear effects on the optical system performance for different shapes of input pulse. Influence of inband interference on system performance is also studied in this paper. BER (Bit Error Probability) for IM-DD (Intensity Modulation – Direct Detection) telecommunication system is obtained for the worst case of interference influence.**

***Keywords* – Chromatic dispersion, Kerr's nonlinearity, Inband Interference, Schrödinger equation, IM-DD system.**

I. INTRODUCTION

In the past, optical losses were the most important limiting factors in optical transmitting systems. Today, in the actual optical systems, dispersive and nonlinear effects restrict speed and transmission length of these systems. Highly nonlinear operating conditions or the interplay between the different linear and nonlinear effects can result in dramatic changes of the temporal and spectral properties of the pulse and thus lead to severe performance degradation.

Propagation of optical pulses in single-mode optical fibers is mainly influenced by the group velocity dispersion and the refractive index nonlinearity. The main contribution to the group velocity dispersion is represented by the parameter β_2, which leads in general to a broadening of the pulse shape. As a pulse widens, it can broaden enough to interfere with neighboring pulses (bits) on the fiber, leading to intersymbol interference. Dispersion thus limits the bit spacing and the maximum transmission rate on a fiber-optic channel. TOD (third-order dispersion) and FOD (forth-order dispersion) are higher-order effects originating from the wavelength dependence of the group velocity dispersion.

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These dispersive effects can also distort ultrashort optical pulses in the linear as well as in nonlinear regime. In a dispersive medium, the index of refraction is a function of the wavelength. Thus, if the transmitted signal consists of more than one wavelength, certain wavelengths will propagate faster than other wavelengths. Since no laser can create a signal consisting of an exact single wavelength, chromatic (material) dispersion will occur in most systems [1], [2]. Second order dispersion has the strongest influence on pulse deformation and higher order dispersions are neglected in its presence. Single-mode optical fiber that works under anomalous dispersive regime is used as transmitting medium in this paper.

An optical signal power transmitted through the optical fiber, long hundreds of kilometers, is in the range of a few mW [3]. Influence of different sort of nonlinear effects had not to be neglected for such optical power values, especially the influence of Kerr's nonlinearity [1]. This nonlinear effect is consequence of refractive index which depends on the pulse intensity. Kerr's nonlinearity is able to decrease pulse deformation produced by chromatic dispersion in anomalous dispersive regime of the optical fiber.

Previous results have shown that shape of fundamental LP_{01} mode in single-mode fiber is similar to Gaussian shape. It is reason why many useful pulses in optical system has Gaussian shape [3]. It is more useful, in some cases, to use Sech shape of pulse [1], especially in nonlinear optical fiber.

The interference is one kind of disturbance that appears in optical telecommunication system and it can be inband or outband, i.e. it can be at the same or at different frequency in relation to a useful signal [4], [5]. Interference is always accumulated when the signal passes through the nodes and can't be eliminated by filters. Since inband interference can't be eliminated by optical filtering in a receiver, its influence on system performance is studied in this paper. This kind of interference can cause fluctuation of signal power which on the other hand can degrade system performances.

All results in this paper are determined by numerically solving Schrödinger equation using symmetrical split-step Fourier method.

II. RECEIVED PULSE

Pulse propagation along the nonlinear optical fiber can be described by Schrödinger equation [1]:

$$\frac{\partial U}{\partial z} = -i\frac{\mathrm{sgn}(\beta_2)}{2L_D}\frac{\partial^2 U}{\partial \tau^2} + \frac{i}{L_{NL}}|U|^2 U \qquad (1)$$

where U is optical pulse envelope. β_2 is known as group-velocity dispersion parameter and defines dispersive regime of optical fiber. L_D and L_{NL} are dispersive and nonlinear length, respectively. In case when dispersive effects along with nonlinear effects affect pulse propagation, these lengths must be equal ($N^2 = L_D/L_{NL} = 1$).

An useful optical pulse at the beginning of optical fiber can be written as:

$$s(0,\tau) = U(0,\tau)\cos(\omega_r \tau) \qquad (2)$$

$\omega_r = \omega T_0$ is normalized frequency and T_0 is pulse width. Inband interference is consequence of using nonideal devices in the optical system. It can appear anywhere along the fiber and it is time and phase shifted in regard to the useful optical pulse. The inband interference can be modeled as:

$$s_i(z_i,\tau) = U_i(z_i,\tau)\cos(\omega_r \tau + \varphi) \qquad (3)$$

U_i is the inband interference envelope, φ is its phase shift and z_i is the place along the optical fiber where the interference appears and

The envelope and phase of the resulting signal at the place where interference appears are simply evaluated as [6]:

$$U_r(z_i,\tau) = \sqrt{U^2(z_i,\tau) + 2U(z_i,\tau)U_i(z_i,\tau)\cos\varphi + U_i^2(z_i,\tau)} \qquad (4)$$

$$\psi(z_i,\tau) = arctg\frac{U_i(z_i,\tau)\sin\varphi}{U(z_i,\tau) + U_i(z_i,\tau)\cos\varphi} \qquad (5)$$

and they represent new initial conditions for solving Schrödinger equation.

The time shape of received optical pulse can be obtained by solving Eq. (1) using symmetrical split-step Fourier method.

III. BIT ERROR PROBABILITY

IM-DD optical telecommunication systems are simple and pay off economically and these are the main reasons for their wide application. If we assume quantum noise to be Gaussian distributed also assume that both symbols (1 and 0) are equally probable, the conditional bit error probability of such system is [3], [7]:

$$P_{e/b} = \frac{1}{2}\left[\int_{V_p}^{+\infty}\frac{1}{\sqrt{2\pi}\sigma_0}\exp\left(-\frac{(y-\bar{y}_0)^2}{2\sigma_0^2}\right)dy + \int_{-\infty}^{V_p}\frac{1}{\sqrt{2\pi}\sigma_1}\exp\left(-\frac{(y-\bar{y}_1)^2}{2\sigma_1^2}\right)dy\right] \qquad (6)$$

where $\bar{y}_0$, $\bar{y}_1$ are mean values of the resulting signals (4) and V_p is the optimal decision threshold:

$$V_p = \frac{\bar{y}_1'\sigma_0 + \bar{y}_0'\sigma_1}{\sigma_0 + \sigma_1} \qquad (7)$$

$\bar{y}_0'$, $\bar{y}_1'$ are mean values of useful signal. The unconditional bit error probability is obtained by averaging relation (6), assuming that $p(b)$ is uniform probability density function of interference time shift:

$$BER = \int_{-\frac{1}{2B}}^{\frac{1}{2B}} P_{e/b}\, p(b)\, db \qquad (8)$$

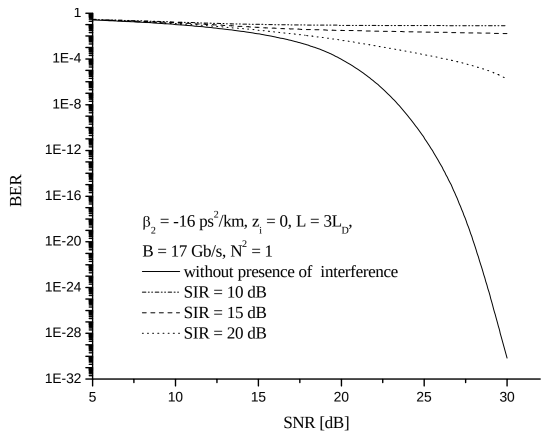
and B is bit rate.

Gaussian pulse is very often found as a useful optical pulse in optical telecommunication systems. Its envelope and envelope of inband interference can be modelled similarly as:

$$U(0,\tau) = a\exp(-\tau^2/2) \qquad (9)$$

$$U_i(z_i,\tau) = a_i\exp(-(\tau-b)^2/2) \qquad (10)$$

Value of parameter a depends on sending information. Parameter a_i shows normalized magnitude of interference and b is time shift of interference.



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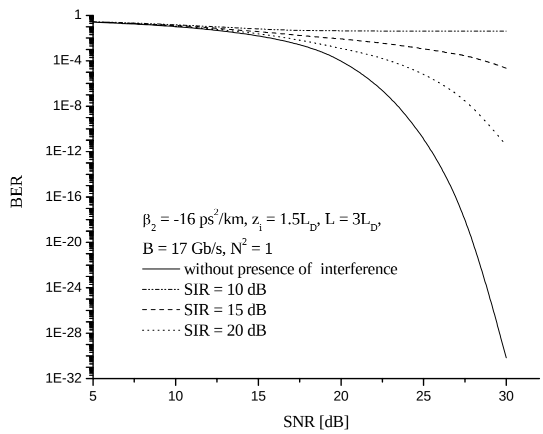


b)

Fig. 1. The bit error probability as function of SNR (Gaussian pulse)

a) $z_i = 0$, *b*) $z_i = L/2$.

Bit error probabilities obtained using Eqs. (1), (4), (5), (6)-(8), (9) and (10) are presented on Fig. 1 (SIR – Signal-to Interference Ratio).

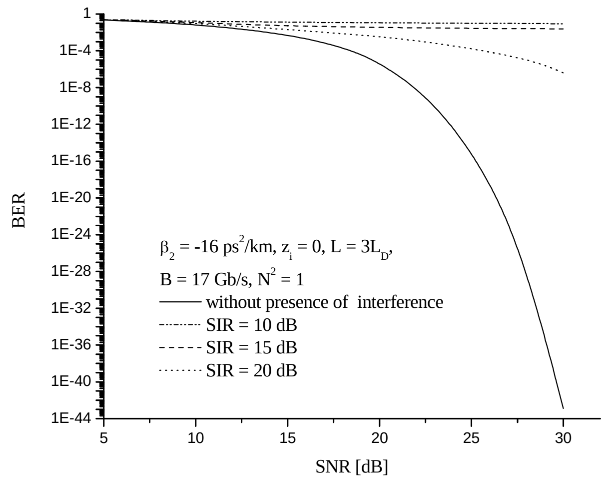
Scientific results showed that Kerr's nonlinearity can decrease pulse deformation induced by second order chromatic dispersion. If we want that Kerr's nonlinearity neutralize that negative influence of dispersive effects we should use pulse with Sech envelope as useful pulse:

$$U(0,\tau) = a \sec h(\tau) \tag{11}$$

The envelope of inband interference has following shape:

$$U_i(z_i,\tau) = a_i \sec h(\tau - b) \tag{12}$$

Fig. 2 shows bit error probability calculated for this case.



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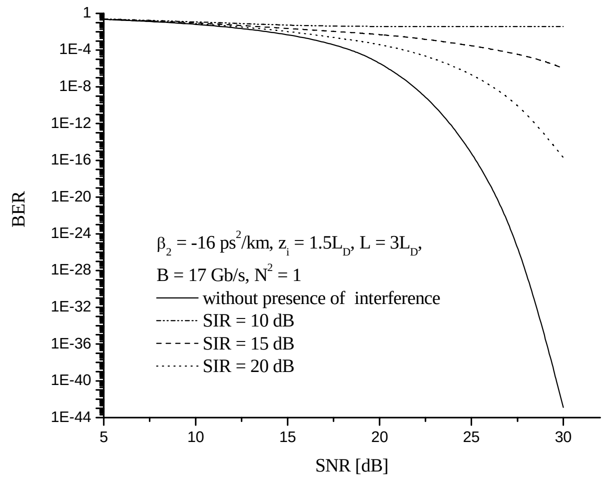

b)

Fig. 2. The bit error probability as function of SNR (Sech pulse) *a*) $z_i = 0$, *b*) $z_i = L/2$.

It can be noticed from both figures that performances of optical systems are the worst when interference appears at the beginning of optical fiber than it appears along the fiber. There is a logical reason for such results. Condition for common influence of dispersive and nonlinear effects, i.e. $N^2 = 1$, is perturbed at the place when interference appears. From this place to the end of optical fiber influence of dispersive effects dominates in the fiber. This is reason for pulse broadening that induces such severe performances of optical system.

Solid lines on Figs. 1 and 2 show BER when Gaussian and Sech pulse propagate along the fiber. For SNR = 30 dB, BER for Sech pulse is 10^{12} times less than for Gaussian pulse. That shows better resistance of Sech pulse to common influence of dispersive and nonlinear effects in the presence of inband interference.

When inband interference appears at the beginning of optical fiber, system performance is better when useful pulse has Gaussian envelope. In the presence of such kind of interference, difference between resulting pulse and useful pulse at the receiver, at the decision time, is less than in case when useful pulse has Sech envelope shape.

Opposite situation happens when inband interference appears along the fiber. Sech pulse maintains its shape to the place when interference appears. Because of that this situation converge to case when Sech pulse propagates along shorter fiber in the presence of inband interference at the beginning of optical fiber. Shorter fiber means less influence of dispersive effects on pulse shape of resulting signal. This is reason for better performance of optical systems that use Sech pulse when the interference appears along the fiber.

In our previous paper we studied how pulse shape influence on system performance in the presence of interference and dispersive effects [8]. In that case better performances are obtained when interference appears at the beginning of optical fiber than somewhere in the middle of the fiber. It was shown in that paper that Sech pulse is more immune to interference influence than Gaussian pulse in both cases of the place of interference occurrence $z_i = 0$ and $z_i = L/2$.

IV. Conclusion

Influence of second order dispersion, Kerr's nonlinearity and inband interference on performance of IM-DD systems is studied in this paper. In optical telecommunication system Gaussian and Sech pulse are very often found as useful pulse. This is reason for using these pulses in our investigation. Calculated BER confirms fact that Kerr's nonlinearity enables propagation Sech pulse along the fiber without great pulse deformation. Inband interference can be very dangerous because it can't be eliminated by optical filtering at the receiver. We considered two cases. First, interference appears at the beginning of optical fiber. Second, interference appears in the middle of the fiber. Results obtained in this paper showed that Sech pulse is more resistant to influence of interference appearing along the fiber than Gaussian pulse. Situation is changed when interference appears at the beginning of the optical fiber. For both useful pulse shapes, system has better performance when interference appears near to the receiver than to the laser.

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