FACTA UNIVERSITATIS (NIŠ)
Series: Electronics and Energetics vol. 14, No. 3, December 2001, 357-373

PERFORMANCE OF IM/DD OPTICAL SYSTEM IN THE PRESENCE OF NOISE AND INTERFERENCE

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Abstract: This paper considers high capacity long-haul optical communication systems. The dispersion compensation, using the compensation fibers, is often applied in such systems. The shape of the impulse at the receiver input is determined by solving the Schrödinger equation. In this paper, we derive the expressions for determining the error probability of intensity-modulation/direct- detection (IM/DD) communication systems in the presence of the noise and interferences. The interferences appear at the transmiter, optical fiber and receiver. The noise sources are the photodetectors and resistances at the receiver

Key words: Optical communication system, error probability, fiber dispersion, Poisson probability function, Gaussian noise.

1. Introduction

Owing to the advent of erbium-doped fiber amplifier (EDFA), fiber loss at 1.55 μm wavelength was overcome. The fiber loss of a long-haul optical communication system can be periodically compensated by the amplifiers. The often-limiting factor at the system is fiber dispersion, which distorts signals. By periodic dispersion compensation one can achieve high-speed and long-haul transmission system. The dispersion compensation can be accomplished by arranging the dispersion of the transmission fiber or by the use of a dispersive element in which its sign of dispersion is opposite to the transmission fiber. For every amplifier spacing the dispersive element can be placed at either the input or output end of the transmission fiber to compensate for the fiber dispersions. The former is called precompensation

Manuscript received January 12, 2001.

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configuration (PRCC) and the latter is called postcompensation configuration (POCC). However, fiber nonlinearities complicate the system design. Because the average dispersion at such systems are low, four- wave mixing (FWM) between signal and amplifier noise is serious. These leads to the distortion of signal, the broadening of signal spectrum, and the increase of noise power which is converted from the signal through FWM. By toiloring the fiber dispersion, the signal-noise FWM can be effectively reduced. On the other hand, signal suffers from pulse distortion owing owing to the residual frequency chirping induced by self-phase modulation (SPM). Fortunately, by properly utilizing SPM to compress the signal pulse, the system performance can be improved. In this paper, we consider bi-end compensation configuration (BECC) in which two dispersive elements are placed at the input and output ends of the transmission fiber, respectively, for every amplifier spacing. The total dispersion of the two dispersive elements is chosen to completely compensate for the accumulated second-order fiber dispersion within amplifier spacing. It is found that, by toiloring the pulse compressibility owing to the combined effect of dispersion and SPM, the system performance can be further improved by the use of BECC.

There are two possible modulation formats, nonre turn-to-zero (NRZ) and return-to-zero (RZ). The question at which format is better is in debate and depends on system design. For the considered system parameters we found that the performance with NRZ format is better than that with RZ format because NRZ format is more robust for the case of long amplifier spacing and ultralong transmission distance. Therefore, NRZ is used in the following. However, the techniques developed in this paper can also be applied to RZ format for the often system designs.

2. Performance of Optical Communication System with Compensating Dispersion

The model of the optical communication system under consideration is shown in Fig. 1.

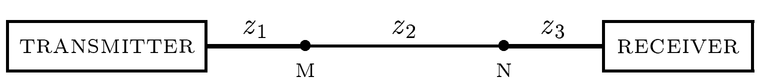


Fig. 1. Optical communicatuon system with compensating dispersion.

The compensating fiber of length z_1 is put between transmitter and point M. The transmitting fiber of length z_2 is between points M and N. Again, the compensating fiber of length z_3 is between point N and receiver.

The complex envelope of the electric field is determined from the Schrödinger equation

$$i\frac{\partial A(t,z)}{\partial z} - \frac{1}{2}\beta_2\frac{\partial^2 A(t,z)}{\partial t^2} + \gamma|A(t,z)|^2 A(t,z) = -i\frac{1}{2}A(t,z) \qquad (1)$$

where $A(t,z)$ is the signal envelope, β_2 represents the second-order dispersion, $\gamma = 2\pi n_2/\lambda A_{eff}$, n_2 is the Kerr coefficient, λ is the carrier wavelength, A_{eff} is the efficient fiber cross section and α is the fiber loss.

The electric field envelope of the input pulse is taken to be

$$A(t) = \sqrt{P}e^{-\frac{t^2}{t_s^2}} \qquad (2)$$

By solving the equation (1), one can obtain the envelope in the point M for the starting condition $A(t,0) = A(t)$ Setting $z = z_1$ in the solution of the propagation equation, we obtain $A(t,z_1)$. The parameter β_2 in this range is negative. The impulse envelope at point N is obtained by solving propagation equation (1) for the starting condition $A(t,0) = A(t,z_1)$ Setting $z = z_2$ in the solution, we obtain the impulse envelope at the point N in the form $A(t,z_2)$. The envelope of the impulse at the receiver input is obtained by solving the equation (1) for the starting condition $A(t,0) = A(t,z_2)$ The envelope at the receiver input $A(t,z_3)$ is obtained for $z = z_3$. The intesitete of the light, exciting the receiver photodiode, is

$$\lambda(t) = c|A(t,z_3)|^2 \qquad (3)$$

The decision is done on the basis of the signal

$$z = an + y \qquad (4)$$

where n is the number of electrons emitted by the photodiode, and y is the Gaussian noise accumulated in resistances and amplifiers in the receiver

$$p(y) = \frac{1}{\sqrt{2\pi}\sigma_y}e^{-\frac{y^2}{2\sigma_y^2}}$$

where σ^2 is the variance of the Gaussian noise.

The conditional probability density function of the signal z is

$$p(z|n) = \frac{1}{\sqrt{2\pi}\sigma_y} e^{-\frac{(z-an)^2}{2\sigma_y^2}}$$

The number of electrons emitted by the photodiode has the Poisson probability function

$$\begin{aligned} P(n) &= \frac{\lambda^n}{n!} e^{-\lambda} \\ &= \frac{c^n |A(t,z_3)|^{2n}}{n!} e^{-c|A(t,z_3)|2} \end{aligned} \tag{5}$$

The probability density function of the signal z is

$$p(z) = \sum_{n=0}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_y} e^{-\frac{(z-an)^2}{2\sigma_y^2}} \frac{c^n |A(t,z_3)|^{2n}}{n!} e^{-c|A(t,z_3)|^2} \tag{6}$$

The envelopes of the transmitting impulses have the forms

$$A_0(t) = \sqrt{P_0} e^{-\frac{t^2}{t_s^2}} \quad \text{for } H_0,$$

and

$$A_1(t) = \sqrt{P_1} e^{-\frac{t^2}{t_s^2}} \quad \text{for } H_1.$$

The likelihood functions of the optical communication system are

$$\begin{aligned} p_0(z) &= \sum_{n=0}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_y} e^{-\frac{(z-an)^2}{2\sigma_y}} \frac{c^n |A_0(t,z_3)|^{2n}}{n!} e^{-c|A_0(t,z_3)|^2}, \quad \text{and} \\ p_1(z) &= \sum_{n=0}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_y} e^{-\frac{(z-an)^2}{2\sigma_y}} \frac{c^n |A_1(t,z_3)|^{2n}}{n!} e^{-c|A_1(t,z_3)|^2} \end{aligned} \tag{7}$$

The error probability of the system is calculated using the expression

$$P_e = P(H_0) \int_{2T}^{\infty} p_0(z)dz + P(H_1) \int_{-\infty}^{2T} p_1(z)dz \tag{8}$$

3. Performance of Optical Communication System with Compensating Dispersion in the Presence of Interference

The model of the optical communication system with compensating dispersion in the presence of the interference appearing at the transmitter output is shown in Fig. 2.

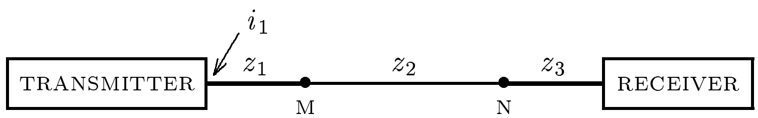


Fig. 2. Optical communication system with the interference accumulated at the transmiter output.

The electrical field of the interference is

$$i_1(t) = I_1 \cos(\omega_0 t + \theta_1) \tag{9}$$

where I_1 is the interference amplitude, and θ_1 is the random phase with the Gaussian probability density function

$$p(\theta_1) = \frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{\theta_1^2}{2\sigma_1^2}}$$

where σ_1^2 is the variance of the phase noise θ_1. The total optical signal at the beginning of the compensating fiber connecting with transmitter is

$$U(t) = A(t) \cos \omega_0 t + I_1 \cos(\omega_0 t + \theta) \tag{10}$$

where the envelope $A(t)$ is given by expression (2). The previous expression can be written in the form

$$u(t) = U_1(t) \cos(\omega_0 t + \varphi_1(t)) \tag{11}$$

where $U_1(t)$ is the envelope given by the expression

$$U_1(t) = \sqrt{A^2(t) + I_1^2 + 2A(t) I_1 \cos \theta_1}$$

and

$$\varphi_1(t) = \arctan \frac{-I_1 \sin \theta_1}{A(t) + I_1 \cos \theta_1}$$

The complex envelope of the signal at the input of the compensating fiber connected with transmiter is

$$U(t) = U_1(t)e^{j\varphi_1(t)} \tag{12}$$

The envelope of the signal at the point M of the optical fiber is obtained by solving the propagation equation (1) for the starting condition

$$A(t, 0) = U(t)$$

Setting $z = z_1$ in the solution we obtain $A(t, z_1)$. The envelope at the point N, $A(t, z_2)$, is obtained by solving the equation (1) for the starting condition $A(t, z_1)$. The envelope $A(t, z_3)$ of the impulse at the receiver input is obtained by solving the propagation equation (1) for the starting condition $A(t, 0) = A(t, z_2)$. The error probability is determined in the similar way as in the previous case using the expression (7) and (8).

Fig. 3 presents the model of the optical communication system with compensating dispersion in the presence of the interference accumulated at the communication fiber.

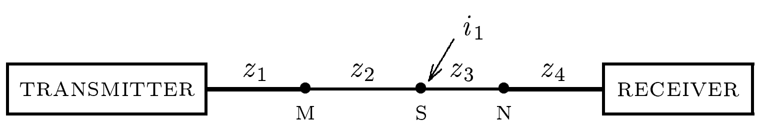


Fig. 3. Optical communication system with the interference accumulated at the communication fiber.

The envelope of the electric field $A(t, z_1)$ at the first compensation fiber output is obtained by solving the propagation equation (1) for the starting condition $A(t, 0) = A(t)$. Two narrowband processes are summed at the point S. The first narrowband process is emitted by the transmitter and its envelope $A(t, z_2)$ is obtained by solving the propagation equation (1) for the starting condition $A(t, 0) = A(t, z_1)$. The envelope $A(t, z_2)$ has the absolute value of envelope $|A(t, z_2)|$ and phase φ_1. The second narrowband process is the interference i_1, given in the form

$$i_1(t) = I_1 \cos(\omega_0 t + \theta_1) \tag{13}$$

where the phase θ_1 has the Gaussian probability density function

$$p(\theta_1) = \frac{1}{\sqrt{2\pi}\sigma_{\theta_1}} e^{-\frac{\theta_1^2}{2\sigma_{\theta_1}^2}}$$

The equivalent envelope at the point S is

$$U(t, z_2) = |U(t, z_2)| e^{j\varphi_2} \tag{14}$$

where

$$|U_1(t, z_2)| = \sqrt{|A(t, z_2)|^2 + I_1^2 + 2|A(t, z_2)| I_1 \cos(\varphi_1 - \theta_1)}$$

and

$$\varphi_2 = -\arctan \frac{|A(t, z_2)| \sin \varphi_1 + I_1 \sin \theta_1}{|A(t, z_2)| \cos \varphi_1 + I_1 \cos \theta_1}$$

The envelope $A(t, z_3)$ at the point N is obtained by solving the propagation equation (1) for the starting condition $A(t, 0) = U(t, z_2)$. The envelope $A(t, z_4)$ is obtained by solving the propagation equation (1) for the starting condition $A(t, 0) = A(t, z_3)$. The likelihood functions and error probability are determined using the expressions (7) and (8).

Fig. 4 presents the model of the optical communication system with compensating dispersion in the presence of interference accumulated at the communication fiber and at the receiver.

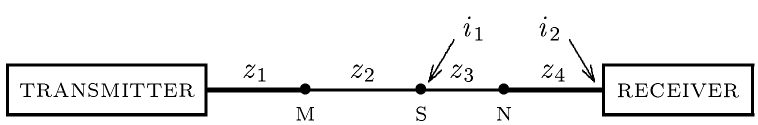


Fig. 4. Optical communication system with interferences accumulated at the receiver and communication fiber.

The interference i_4 is modeled by sinusoidal wave with the random phase that has Gaussian probability density function

$$i_4 = I_2 \cos \theta_2$$

where

$$p(\theta_2) = \frac{1}{\sqrt{2\pi}\sigma_{\theta_2}} e^{-\frac{\theta_2^2}{2\sigma_{\theta_2}^2}}$$

The decision is made on the basis of the signal

$$\begin{aligned} z =& an + y + i_4 \\ =& an + y + I_2 \cos\theta_2 \end{aligned}$$

where n is the number of electrons emitted by the photodiode, and y is the Gaussian noise. The conditional probability density function of the signal z is

$$p(z) = \frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{(z-an-I_2\cos\theta_2)^2}{2\sigma_1^2}} \tag{15}$$

The probability function of the number of the electrons emitted by the photodiode is

$$P(n) = \frac{\lambda^n}{n!} e^{-\lambda}$$

For the model presented in Fig. 4, the intesite of the light exciting the photodiode is

$$\lambda = |A(t, z_4)|^2.$$

The likelihood functions of the optical communication system presented in Fig. 4 are

$$\begin{aligned} p_0(z) =& \int_{-\pi}^{\pi} d\theta_2 \sum_{n=0}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{(z-an-I_2\cos\theta_2)^2}{2\sigma_1^2}} \frac{c^n|A_0(t,z_4)|^{2n}}{n!} e^{-c|A_0(t,z_4)|^2} \\ & \times \frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{\theta_2^2}{2\sigma_{\theta_2}^2}} \\ p_1(z) =& \int_{-\pi}^{\pi} d\theta_2 \sum_{n=0}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{(z-an-I_2\cos\theta_2)^2}{2\sigma_1^2}} \frac{c^n|A_1(t,z_4)|^{2n}}{n!} e^{-c|A_1(t,z_4)|^2} \\ & \times \frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{\theta_2^2}{2\sigma_{\theta_2}^2}} \end{aligned} \tag{16}$$

The error probability is determined using the expression (8). Let the modal noise is also present in the communication system shown in Fig. 4.

Mixing modes causes the modal noise and it appears at the communication fiber. The amplitude values of the modal noise have the Gaussian probability density function. The intesitet of the light exciting the photodiode is

$$\lambda = c[|A(t, z_4)| + x]^2$$

The conditional probability function of the number of the electrons emitted by the photodiode is

$$\begin{aligned} P(n|x) &= \frac{\lambda^n}{n!} e^{-\lambda} \\ &= \frac{c^n [|A_0(t, z_4)| + x]^{2n}}{n!} e^{-c[|A_0(t,z_4)|+x]^2} \end{aligned}$$

Using the expression (15), we obtain the likelihood functions of the system

$$\begin{aligned} p_0(z) &= \int_{-\infty}^{\infty} dx \int_{-\pi}^{\pi} d\theta_2 \sum_{n=0}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{(z-an-I_2\cos\theta_2)^2}{2\sigma_1^2}} \\ &\quad \times \frac{c^n [|A_0(t, z_4)| + x]^{2n}}{n!} e^{-c(|A_0(t,z_4)|+x)^2} \\ &\quad \times \frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{\theta_2^2}{2\sigma_{\theta_2}^2}} \frac{1}{\sqrt{2\pi}\sigma_x} e^{-\frac{x^2}{2\sigma_x^2}} \\ p_1(z) &= \int_{-\infty}^{\infty} dx \int_{-\pi}^{\pi} d\theta_2 \sum_{n=0}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{(z-an-I_2\cos\theta_2)^2}{2\sigma_1^2}} \\ &\quad \times \frac{c^n [|A_1(t, z_4)| + x]^{2n}}{n!} e^{-c(|A_1(t,z_4)|+x)^2} \\ &\quad \times \frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{\theta_2^2}{2\sigma_{\theta_2}^2}} \frac{1}{\sqrt{2\pi}\sigma_x} e^{-\frac{x^2}{2\sigma_x^2}} \end{aligned} \tag{17}$$

Now we observe the case of optical communication system presented in Fig. 3 when the interference is modeled by the sum of the sinusoidal waves

$$i_1 = \sum_{i=1}^{p} I_i \cos(\omega_0 t + \theta_i)$$

where

$$p(\theta_i) = \frac{1}{\sqrt{2\pi}\sigma_i} e^{-\frac{\theta_i^2}{2\sigma_i^2}}$$

The electrical field, at the point S in Fig. 3, that emitted by the transmitter is

$$u_s(t) = |A(t, z_2)| \cos(\omega_0 t + \varphi_1)$$

The total electrical field at the point S is

$$\begin{aligned} U(t, z_2) =& |A(t, z_2)| \cos(\omega_0 t + \varphi_1) + \sum_{i=1}^{p} I_i \cos(\omega_0 t + \theta_1) \\ =& \, |U(t, z_2)| \cos(\omega_0 t + \varphi_2) \end{aligned} \tag{18}$$

where

$$|U(t, z_2)| = \sqrt{\begin{matrix} |A(t, z_2)|^2 + \sum_{i=1}^{p} I_i^2 + \sum_{i=1}^{p} 2|A(t, z_2)| I_i \cos(\varphi_i - \theta_i) \\ + \sum_{i=1}^{p} \sum_{j=1}^{p} 2 I_i I_j \cos(\theta_i - \theta_j) \end{matrix}}$$

and

$$\varphi_2 = -\arctan \frac{|A(t, z_2)| \sin \varphi_1 + \sum_{i=1}^{p} I_i \sin \theta_i}{|A(t, z_2)| \cos \varphi_1 + \sum_{i=1}^{p} I_i \cos \theta_i}$$

The envelope $A(t, z_4)$ is determined, based on the previous case, and likelihood functions and error probability are determined on the basis of (7) and (8).

4. Performance of Optical Communication System with Compensating Dispersion with Multiwave Carrier Signals

We observe the model of the optical communication system presented in Fig. 1. The transmitter sends two modulated carriers with envelopes $A(t)$ and $B(t)$

$$A(t) = \sqrt{P_A} e^{-\frac{t^2}{t_s^2}}$$

$$B(t) = \sqrt{P_B} e^{-\frac{t^2}{t_s^2}}$$

The system of the propagation differential equations determining the envelopes $A(t,z)$ and $B(t,z)$ in time and at distance are

$$\begin{aligned} i\frac{\partial A(t,z)}{\partial z} - \frac{1}{2}\beta_2\frac{\partial^2 A(t,z)}{\partial t^2} + \gamma[|A(t,z)|^2 + |B(t,z)|^2]A(t,z) \\ = -i\frac{1}{2}\alpha A(t,z) \\ i\frac{\partial B(t,z)}{\partial z} - \frac{1}{2}\beta_2\frac{\partial^2 B(t,z)}{\partial t^2} + \gamma[|A(t,z)|^2 + |B(t,z)|^2]B(t,z) \\ = -i\frac{1}{2}\alpha B(t,z) \end{aligned} \tag{19}$$

The values of envelope $A(t,z_1)$ and $B(t,z_1)$ at the point M at the distance z_1 from the transmitter are determined by solving the differential equations (19) for the starting conditions $A(t,0) = A(t)$ and $B(t,0) = B(t)$. The values of the envelopes $A(t,z_2)$ and $B(t,z_2)$ at the point N are determined by solving the system of equations (19) for the starting conditions $A(t,0) = A(t,z_1)$ and $B(t,0) = B(t,z_1)$. The values of the envelopes $A(t,z_3)$ and $B(t,z_3)$ at the receiver input are determined by solving the system (9) for the starting conditions $A(t,0) = A(t,z_2)$ and $B(t,0) = B(t,z_2)$.

Let the modal noise is present in the fiber and sinusoidal interference appears in the receiver. The decision is made on the basis of the signal

$$z = an + y + I_2\cos\theta_2 \tag{20}$$

The probability for n is Poisson

$$P(n) = \frac{\lambda_A^2}{n!}e^{-\lambda_A}$$

for the first channel and

$$P(n) = \frac{\lambda_B^2}{n!}e^{-\lambda_B}$$

for the second channel where $\lambda_A = c[|A(t,z_4)|^2 + x]$ and $\lambda_B = c[|B(t,z_4)|^2 + x]$.

The likelihood functions are calculated using expression (20) and for the first channel they are

$$
\begin{aligned}
p_0(z) = \int\limits_{-\infty}^{\infty} dx \int\limits_{-\pi}^{\pi} d\theta_2 \frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{(z-an-I_2\cos\theta_2)^2}{2\sigma_1^2}} \\
\times \frac{c^n[|A_0(t,z_4)|+x]^n}{n!} e^{-c(|A_0(t,z_4)|+x)^2} \\
\times \frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{\theta_2^2}{2\sigma_{\theta_2}^2}} \frac{1}{\sqrt{2\pi}\sigma_x} e^{-\frac{x^2}{2\sigma_x^2}} \\
p_1(z) = \int\limits_{-\infty}^{\infty} dx \int\limits_{-\pi}^{\pi} d\theta_2 \frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{(z-an-I_2\cos\theta_2)^2}{2\sigma_1^2}} \\
\times \frac{c^n[|A_1(t,z_4)|+x]^n}{n!} e^{-c(|A_1(t,z_4)|+x)^2} \\
\times \frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{\theta_2^2}{2\sigma_{\theta_2}^2}} \frac{1}{\sqrt{2\pi}\sigma_x} e^{-\frac{x^2}{2\sigma_x^2}}
\end{aligned}
\qquad (21)
$$

The likelihood functions for the second channel are

$$
\begin{aligned}
p_0(z) = \int\limits_{-\infty}^{\infty} dx \int\limits_{-\pi}^{\pi} d\theta_2 \frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{(z-an-I_2\cos\theta_2)^2}{2\sigma_1^2}} \\
\times \frac{c^n[|B_0(t,z_4)|+x]^n}{n!} e^{-c(|B_0(t,z_4)|+x)^2} \\
\times \frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{\theta_2^2}{2\sigma_{\theta_2}^2}} \frac{1}{\sqrt{2\pi}\sigma_x} e^{-\frac{x^2}{2\sigma_x^2}} \\
p_1(z) = \int\limits_{-\infty}^{\infty} dx \int\limits_{-\pi}^{\pi} d\theta_2 \frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{(z-an-I_2\cos\theta_2)^2}{2\sigma_1^2}} \\
\times \frac{c^n[|B_1(t,z_4)|+x]^n}{n!} e^{-c(|B_1(t,z_4)|+x)^2} \\
\times \frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{\theta_2^2}{2\sigma_{\theta_2}^2}} \frac{1}{\sqrt{2\pi}\sigma_x} e^{-\frac{x^2}{2\sigma_x^2}}
\end{aligned}
\qquad (22)
$$

Using expression (8), we determine the error probability for the first and second channel

For the model of the communication system presented in Fig. 4, the transmitted WDM signal consists of three carriers. The envelopes of the signals sent by the transmitter are

$$A(t) = \sqrt{P_A} e^{-\frac{t^2}{t_s^2}}$$
$$B(t) = \sqrt{P_B} e^{-\frac{t^2}{t_s^2}}$$
$$C(t) = \sqrt{P_C} e^{-\frac{t^2}{t_s^2}}$$

The system of differential equations determining the envelopes $A(t,z)$, $B(t,z)$ and $C(t,z)$ in time an on distance from the transmitter are

$$\begin{aligned} i\frac{\partial A(t,z)}{\partial z} - \frac{1}{2}\beta_2\frac{\partial^2 A(t,z)}{\partial t^2} + \gamma[|A(t,z)|^2 + |B(t,z)|^2 + |C(t,z)|^2]A(t,z) \\ = -i\frac{1}{2}\alpha A(t,z) \\ i\frac{\partial B(t,z)}{\partial z} - \frac{1}{2}\beta_2\frac{\partial^2 B(t,z)}{\partial t^2} + \gamma[|A(t,z)|^2 + |B(t,z)|^2 + |C(t,z)|^2]B(t,z) \\ = -i\frac{1}{2}\alpha B(t,z) \\ i\frac{\partial C(t,z)}{\partial z} - \frac{1}{2}\beta_2\frac{\partial^2 C(t,z)}{\partial t^2} + \gamma[|A(t,z)|^2 + |B(t,z)|^2 + |C(t,z)|^2]C(t,z) \\ = -i\frac{1}{2}\alpha C(t,z) \end{aligned} \tag{23}$$

The envelopes at the point M on the distance z_1 from the transmitter $A(t,z_1)$, $B(t,z_1)$ and $C(t,z_1)$ are determined by solving the system of equations (48) for the starting conditions

$$\begin{aligned} A(t,0) &= \sqrt{P_A} e^{-\frac{t^2}{t_s^2}} + \sqrt{P_A} e^{-\frac{(t+T)^2}{t_s^2}} + \sqrt{P_A} e^{-\frac{(t-T)^2}{t_s^2}} \\ B(t,0) &= \sqrt{P_B} e^{-\frac{t^2}{t_s^2}} + \sqrt{P_B} e^{-\frac{(t+T)^2}{t_s^2}} + \sqrt{P_B} e^{-\frac{(t-T)^2}{t_s^2}} \\ C(t,0) &= \sqrt{P_C} e^{-\frac{t^2}{t_s^2}} + \sqrt{P_C} e^{-\frac{(t+T)^2}{t_s^2}} + \sqrt{P_C} e^{-\frac{(t-T)^2}{t_s^2}}. \end{aligned} \tag{24}$$

The signals emitted by the transmitter $A(t,0)$, $B(t,0)$ and $C(t,0)$ are given by the expressions (24) in order to emphasize the influence of intersymbol interference on the error probability. The envelopes of the signal at the point S coming from the transmitter are determined by solving the system of equation (48) for the starting conditions $A(t,0) = A(t,z_1)$, $B(t,0) = B(t,z_1$ and $C(t,0) = C(t,z_1)$ In this way we obtain the envelopes $A(t,z_2)$, $B(t,z_2)$ and $C(t,z_2)$. Let the interference i_2 at the point S be on the wavelength with the first channel. Then is

$$U(t,z_2) = |U(t,z_2)|e^{j\varphi_2}$$

where

$$|U_1(t,z_2)| = \sqrt{|A(t,z_2)|^2 + I_1^2 + 2|A(t,z_2)|I_1\cos(\varphi_1 - \theta_1)}$$

and

$$\varphi_2 = -\arctan\frac{|A(t,z_2)|\sin\varphi_1 + I_1\sin\theta_1}{|A(t,z_2)|\cos\varphi_1 + I_1\cos\theta_1}$$

The envelopes $A(t,z_3)$, $B(t,z_3)$ and $C(t,z_3)$ are determined by solving the system of equations (23) for the starting conditions $A(t,0) = U(t,z_2)$, $B(t,0) = B(t,z_2)$ and $C(t,0) = C(t,z_2)$. The envelopes $A(t,z_4)$, $B(t,z_4)$ and $C(t,z_4)$ are determined by solving the system (23) for the starting conditions $A(t,0) = A(t,z_3)$, $B(t,0) = B(t,z_3)$ and $C(t,0) = C(t,z_3)$.

The likelihood functions of the system for the first channel are

$$p_0(z) = \sum_{n=0}^{\infty}\frac{1}{\sqrt{2\pi}\sigma_1}e^{-\frac{(z-cn)^2}{2\sigma_1^2}}\frac{a^n|A_0(t,z_4)|^{2n}}{n!}e^{-a|A_0(t,z_4)|^2}$$
$$p_1(z) = \sum_{n=0}^{\infty}\frac{1}{\sqrt{2\pi}\sigma_1}e^{-\frac{(z-cn)^2}{2\sigma_1^2}}\frac{a^n|A_1(t,z_4)|^{2n}}{n!}e^{-a|A_1(t,z_4)|^2}.$$

The likelihood functions of the system for the second channel are

$$\begin{aligned} p_0(z) &= \sum_{n=0}^{\infty}\frac{1}{\sqrt{2\pi}\sigma_1}e^{-\frac{(z-cn)^2}{2\sigma_1^2}}\frac{a^n|B_0(t,z_4)|^{2n}}{n!}e^{-a|B_0(t,z_4)|^2} \\ p_1(z) &= \sum_{n=0}^{\infty}\frac{1}{\sqrt{2\pi}\sigma_1}e^{-\frac{(z-cn)^2}{2\sigma_1^2}}\frac{a^n|B_1(t,z_4)|^{2n}}{n!}e^{-a|B_1(t,z_4)|^2}. \end{aligned} \tag{25}$$

The likelihood functions of the system for the third channel are

$$\begin{aligned} p_0(z) &= \sum_{n=0}^{\infty}\frac{1}{\sqrt{2\pi}\sigma_1}e^{-\frac{(z-cn)^2}{2\sigma_1^2}}\frac{a^n|C_0(t,z_4)|^{2n}}{n!}e^{-a|C_0(t,z_4)|^2} \\ p_1(z) &= \sum_{n=0}^{\infty}\frac{1}{\sqrt{2\pi}\sigma_1}e^{-\frac{(z-cn)^2}{2\sigma_1^2}}\frac{a^n|C_1(t,z_4)|^{2n}}{n!}e^{-a|C_1(t,z_4)|^2} \end{aligned} \tag{26}$$

The error probability for any channel is determined by using the expression (8).

Fig. 5 present the dependence of impulse shape variations on optical fiber length. The WDM system with two carriers is observed. Figs. 5(a) and 5(b) present the dependence of impulse shape variations on optical fiber length for positive phase constant and in the case without interference, for one and two carriers, respectively.

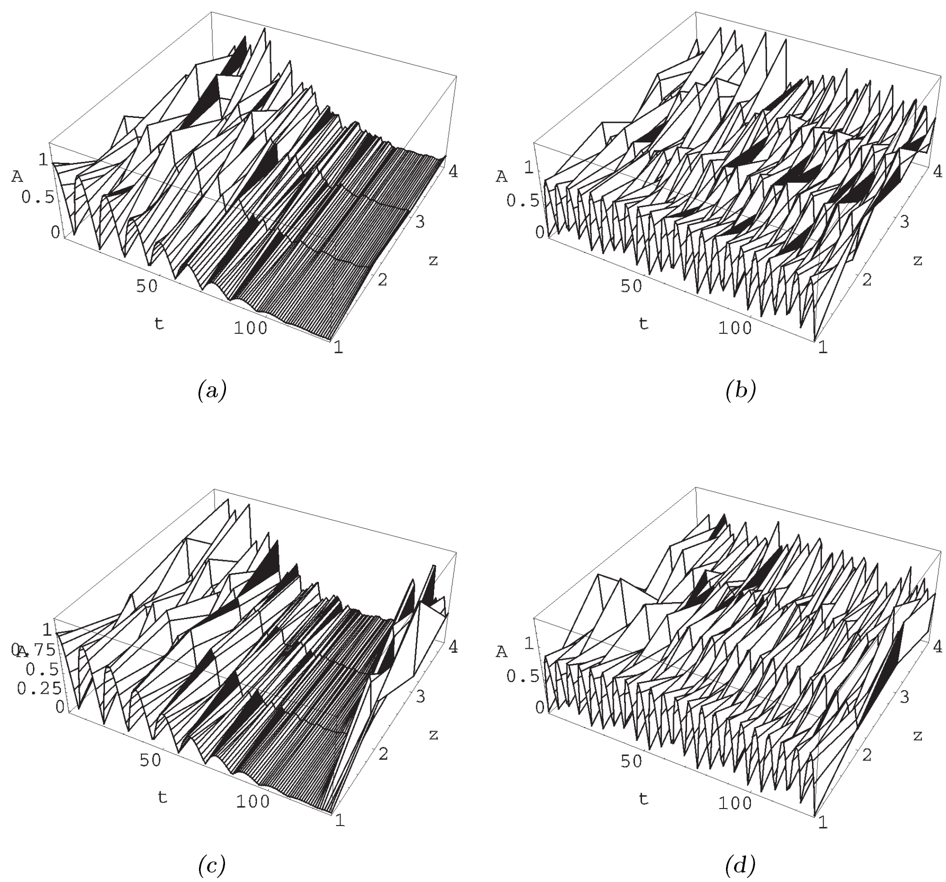
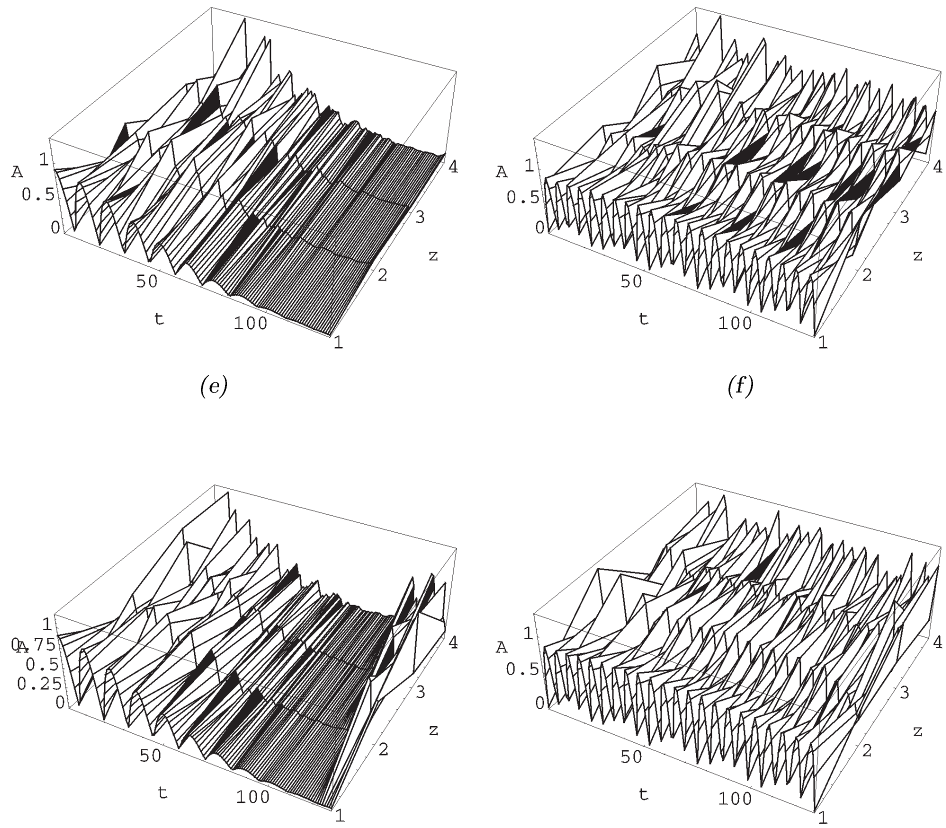


Fig. 5. Dependence of impulse shape variations on optical fiber length:
(a) the pulse shape variation for first carrier and for $\beta = 4$,
(b) the pulse shape variation for second carried and for $\beta = 4$,
(c) the pulse shape variation for first carrier with interference and for $\beta = 4$,
(d) the pulse shape variation for second carrier with interfernce and for $\beta = 4$,



(e) (f)

(g) (h)

Fig. 5. Continue:
(e) the pulse shape variation for first carrier and for $\beta = -4$,
(f) the pulse shape variation for second carried and for $\beta = -4$,
(g) the pulse shape variation for first carrier with interference and for $\beta = -4$,
(h) the pulse shape variation for second carrier with interfernce and for $\beta = -4$,

Figs. 5(c) and 5(b) present the dependence of impulse shape variations on optical fiber length for positive phase constant and in the case with interference, for one and two carriers, respectively.

Figs. 5(e) and 5(f) present the dependence of impulse shape variations on optical fiber length for negative phase constant and in the case without interference, for one and two carriers, respectively.

Figs. 5(g) and 5(h) present the dependence of impulse shape variations on optical fiber length for negative phase constant and in the case with interference, for one and two carriers, respectively.

5. Conclusion

In this paper, we consider the baseband optical communication systems with attenuation and dispersion compensation. Those systems are long haul and high capacity systems. The dispersion compensation is done using the compensating fibers that are placed between amplifiers. We consider the case when two compensating fibers are used. For such systems we derive the likelihood functions and determine the error probability, taking into account the noise and interferences caused by crosstalk. The most significant destructive effects in baseband optical communication systems are the noise in the receiver, as well as the interferences in the transmiter, optical fiber and receiver. The quantum noise, formed in the photodiode, also is the significant negative effect constraining the system performance. This noise has the Gaussian probability distribution. The second significant noise is Gaussian noise, formed in the resistances and amplifiers. The interferences caused by crosstalk are also very important in the optical communication systems. These interferences are modeled by the sinusoidal waves with uniformly distributed random phases. In the paper, we determine the performance of the systems for all these cases.

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