Influence of Residual Laser Radiation on Performance of IM/DD Optical Communication System

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Abstract - **In this paper we determine the performance of intensity-modulation/direct-detection optical communication system for various values of laser extinction ratio and bit rate. The bit error probability dependencies on optical signal peak power are given for optimally chosen threshold. We determine the numerical values of required peak average optical signal power in order to reach the bit error probability 10^{-9}, and present the exact penalties due to finite extinction ratio. The receiver with PIN photodiode is observed in the analysis.**

Keywords - **Optical communications, Extinction ratio, Error probability**

I. Introduction

Since their introduction in the 1960's, optical communication systems have been very actual in numerous scientific researches, [1-8]. Due to the evident superiority of the optical communication systems over the classical wire ones, the great financial resources have been invested into the development and fabrication of the optical fibers, amplifiers, transmitters and receivers, [1-2]. On the basis of some predictions, this decade will be decade of the optical communication system domination, [6]. Regardless the intensity-modulation/direct-detection (IM/DD) optical communication systems have some less good performance then the coherent optical communication systems, [1], [5], due to the clear fact that the receivers for the coherent optical systems are much more complex then the receivers for IM/DD optical communication systems and very fast development of technology for optical amplifier production, IM/DD optical communication systems are mainly incorporated in the domestic and international optical commercial networks, [1-2].

One of the predominant factors, influencing the performance of the optical communication systems for great bit rates, is the so-called extinction ratio e. Namely, most transmitters even in the off state (when binary zero is transmitted) emit some power. In the case of semiconductor lasers, the off-state peak power P_n depends on the bias current I_b and the threshold current I_{th}. If $I_b<I_{th}$, the power emitted during 0 bits is due to spontaneous emission, and generally $P_n<<P_s$, where P_s is the on-state peak power (signal peak power when binary one is transmitted). By contrast, P_n can be significant fraction of P_s if the laser is based close to but above threshold. The extinction ratio is defined as the ratio between the optical peak signal power emitted by the transmitter when the binary zero is transmitted and the optical peak signal power emitted by the transmitter when the binary one is transmitted, [3-4], [7]. The influence of this residual laser radiation is very significant for the quality of information transmission over the optical communication systems, [3-4], [7].

The degradation of the performance of the IM/DD optical communication system, containing the avalanche photodiode for optical signal detection, is determined in [3]. In that paper, the analytical expressions in the closed form are derived for the optimum avalanche gain in the presence of finite extinction ratio and representative numerical results are given. The paper [4] presents the performance of coherent optical synchronous and asynchronous receiver in the presence of the residual laser radiation.

By contrast to those papers, this paper determines the performance of the optical receiver containing the PIN photodiode for direct detection of the intensity modulated binary optical signal. Except the residual laser radiation, the effects considered in the paper are: the photodiode shot noise, photodiode dark current and thermal noise of the amplifier in electrical domain. These effects are modeled in the way presented in [5].

II. System model and analysis

The optical receiver under consideration is presented in Fig. 1. As it was mentioned above, when a binary zero is transmitted, the transmitter laser radiates some power and this residual laser radiation is characterized by the extinction ratio defined by

$$e=\frac{P_n}{P_s}, \qquad 0\le e<1, \tag{1}$$

where P_n and P_s (J/s) are, respectively, the optical signal peak powers corresponding to a binary zero and a binary one.

The optical signal exciting the PIN photodiode, which is the constituent part of the receiver, can be presented in the form

$$S=\sqrt{P_s}e^{j\omega_0 t}$$

when a binary one is transmitted, and

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$$S = \sqrt{eP_s}\, e^{j\omega_0 t}$$

when a binary zero is transmitted, where $\omega_0 = 2\pi\nu$ is the angular frequency, and e is the laser extinction ratio. For the purpose of the analysis we assume the rectangular pulse shape of the signal exciting the detector.

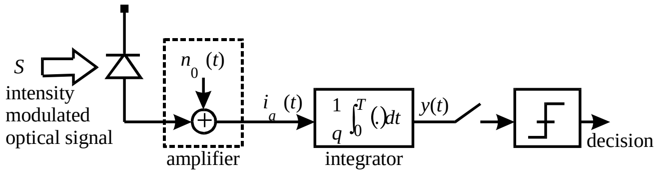

Fig.1. Model of receiver for direct detection of intensity modulated optical signal

The average number of photons, exciting the photodiode during a bit interval, is

$$M_1 = \frac{P_s T}{h\nu},$$

when a binary one is transmitted, and

$$M_0 = \frac{eP_s T}{h\nu},$$

when a binary zero is transmitted, where T is a bit duration given by

$$T = \frac{1}{R_b}, \tag{2}$$

where R_b is the bit rate.

The shot noise $n_{sh}(t)$ is presented at the photodiode output. Under some conditions that are satisfied in practice, [5], shot noise is assumed to be a Gaussian process with equal mean value and variance given by

$$\frac{\eta P_s T}{h\nu}$$

when a binary one is transmitted, and

$$\frac{\eta e P_s T}{h\nu}$$

when a binary zero is transmitted. η is the efficiency of the PIN photodiode used in the optical receiver.

The electrical signal, at the photodiode output, excites the amplifier, which is modeled as the noise source, [5], so the amplifier output signal has the form

$$i_a(t) = RP_s + n_{sh}(t) + n_o(t)$$

when a binary one is transmitted, and

$$i_a(t) = ReP_s + n_{sh}(t) + n_o(t),$$

when a binary zero is transmitted. R is the responsivity of the photodiode defined by, [5],

$$R = \frac{\eta q}{h\nu}, \tag{3}$$

where q is an electron charge.

$n_o(t)$ represents other kinds of noise including the dark current and amplifier thermal noise. The integrator output signal y, being relevant for decision, is

$$y = \frac{1}{q}\int_0^T i_a(t)\,dt.$$

The random process y has the Gaussian probability density function, [5], whose mean value and variance are, respectively,

$$m_1 = \frac{\eta P_s T}{h\nu} \tag{4a}$$

$$\sigma_1^2 = \frac{I_{dk}}{q/T} + \frac{N_{th}}{q^2/T} + m_1 \tag{4b}$$

when a binary one is transmitted, and

$$m_0 = \frac{\eta e P_s T}{h\nu} \tag{5a}$$

$$\sigma_0^2 = \frac{I_{dk}}{q/T} + \frac{N_{th}}{q^2/T} + m_0 \tag{5b}$$

when a binary zero is transmitted.

Hence, the probability density function of the signal y is

$$p_1(y) = \frac{1}{\sqrt{2\pi}\sigma_1} e^{-(y-m_1)/(2\sigma_1^2)}, \tag{6}$$

when a binary one is transmitted, and

$$p_0(y) = \frac{1}{\sqrt{2\pi}\sigma_0} e^{-(y-m_0)/(2\sigma_0{}^2)}, \tag{7}$$

when a binary zero is transmitted.

The bit error probability during detection is determined in the classical way, [1],

$$BER = P_0 \int_{-\infty}^{b} p_1(y)dy + P_1 \int_{b}^{\infty} p_0(y), \tag{8}$$

where $P_0 = P_1 = 1/2$ are the probabilities of a binary zero or one sending. b is the optimum threshold determined under the condition that the bit error probability is minimal. This threshold is the positive solution of the equation

$$p_0(y) = p_1(y), \tag{9}$$

i.e. it is the positive intersection of $p_0(y)$ and $p_1(y)$.

After some mathematical manipulations the expression for the bit error probability can be written in the form

$$BER = 0.25\left(erfc\left(\frac{m_1 - b}{\sqrt{2}\sigma_1}\right) + erfc\left(\frac{b - m_0}{\sqrt{2}\sigma_0}\right)\right). \tag{10}$$

The penalty Δ (dB), which must be paid when the laser extinction ratio is not equal to zero, is defined as the logarithmic ratio between the optical signal peak power P_{sk} when the laser extinction ratio is equal to given value and the optical signal peak power P_{s0} when the laser extinction ratio is equal to zero (both optical signal peak powers are required for achieving given bit error probability):

$$\Delta = 10 \log \frac{P_{sk}}{P_{s0}}. \tag{11}$$

III. NUMERICAL RESULTS

Using the expressions (1)-(10) and numerical values of parameters given in Table 1, we determine the bit error probability dependencies on peak power of the optical signal exciting the PIN photodiode (the assumption is that the signal pulse has the rectangular shape over a bit interval). These dependencies are presented in Figs. 2 and 3 for different values of the laser extinction ratio and bit rates. Fig. 4 shows the dependencies of required received peak power (for achieving the bit error probability $BER=10^{-9}$) on bit rate, for different values of the laser extinction ratio. The concrete numerical values are given in Table 2. From the expression (11) we calculate the penalties due to the finite extinction ratio in order to achieve the bit error probability $BER=10^{-9}$ and give the representative numerical values in Table 3.

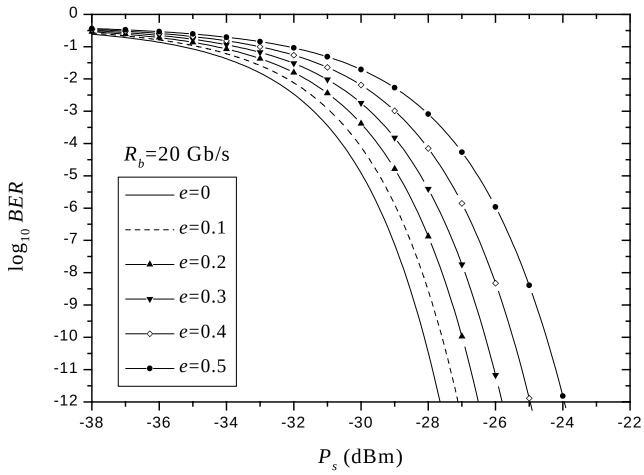

Fig. 2. Error probability dependencies on received peak power for different values of laser extinction ratio

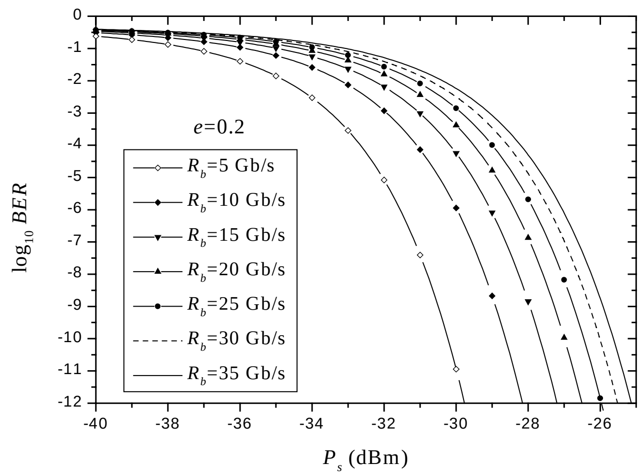

Fig. 3. Bit error probability dependencies on received peak power for different values of bit rates

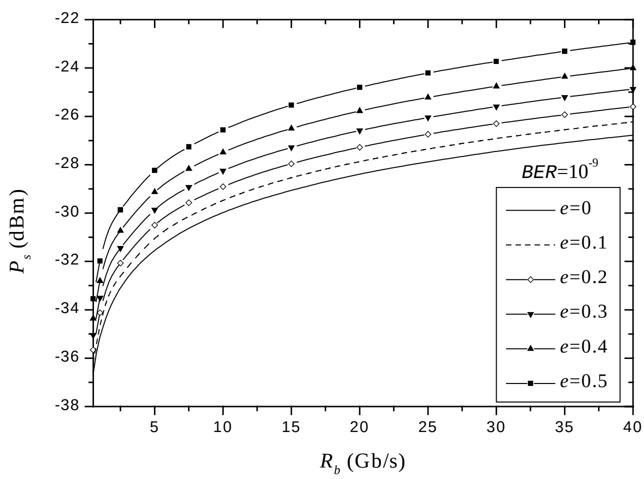

Fig. 4. Required optical signal peak power dependence on bit rate for different values of laser extinction ratio ($BER=10^{-9}$)

TABLE 1. NUMERICAL VALUES OF PARAMETERS USED IN CALCULATIONS

Planck's constant:	h=6.626·10^{-34} J·s
Wavelength:	λ=1552.524 nm
Efficiency of PIN photodiode:	η=1
Power spectrum density of thermal noise:	N_{th}=1 pA^2/Hz
Dark current:	I_{dk}=10 nA
Speed of light in vacuum:	c≈3·10^8 m/s
Electron charge:	q=1.60219·10^{-19} C

TABLE 2. REQUIRED OPTICAL SIGNAL PEAK POWER P_S (dBm) FOR REACHING THE BIT ERROR PROBABILITY BER=10^{-9} IN THE CASE OF DIFFERENT VALUES OF LASER EXTINCTION RATIO e AND BIT RATES R_b (Gb/s)

R_b /e	0	0.1	0.2	0.3	0.4	0.5
0.5	-36.64	-36.18	-36.65	-35.05	-34.36	-33.54
1	-35.12	-34.65	-34.12	-33.51	-32.81	-31.98
5	-31.55	-31.05	-30.50	-29.87	-29.13	-28.24
10	-29.98	-29.48	-28.91	-28.25	-27.49	-26.56
15	-29.06	-28.54	-27.96	-27.29	-26.50	-25.54
20	-28.39	-27.87	-27.28	-26.59	-25.78	-24.80
25	-27.88	-27.35	-26.74	-26.05	-25.22	-24.21
30	-27.45	-26.92	-26.30	-25.60	-24.76	-23.73
35	-27.09	-26.55	-25.93	-25.21	-24.36	-23.31
40	-26.78	-26.23	-25.60	-24.87	-24.01	-22.94

TABLE 3. PENALTY Δ (dB) FOR REACHING BIT ERROR PROBABILITY BER=10^{-9} IN THE CASE OF DIFFERENT VALUES OF LASER EXTINCTION RATIO e AND BIT RATES R_b (Gb/s)

R_b / e	0.1	0.2	0.3	0.4	0.5
0.5	0.46	0.99	1.59	2.28	3.10
1	0.47	1.00	1.61	2.31	3.14
5	0.50	1.05	1.68	2.42	3.31
10	0.50	1.07	1.73	2.49	3.42
15	0.52	1.10	1.77	2.56	3.52
20	0.52	1.11	1.80	2.61	3.59
25	0.53	1.14	1.83	2.66	3.67
30	0.53	1.15	1.85	2.69	3.72

IV. CONCLUSION

Based on the analytical expressions previously derived, we determine the performance of the IM/DD optical receiver containing PIN photodiode for direct detection of the intensity modulated optical signal. The emphasis is placed on determining the influence of the residual laser radiation during binary zero transmission, in combination with influences of the photodiode shot noise and dark current, as well as the thermal noise of the amplifier in electrical domain. We present the bit error probability dependencies on optical signal peak power for different real life bit rates and extinction ratio values. In addition, we present the required optical signal peak power values for reaching the bit error probability BER=10^{-9}, which is the standard in most optical communication systems. Finally, we determine the penalties in order to reach required bit error probability BER=10^{-9} when the extinction ratio is not equal to zero.

The obtained results clearly show that the residual laser radiation has the considerable influence on the performance of the IM/DD optical communication system with PIN photodiode, what must be taken into consideration during designing practical optical communication systems.

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