Performance Analysis of Optical CDMA Systems Using APD for Two Types of Receiver Structures in the Presence of Interference and Receiver Noise

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Abstract-**In this paper, a rigorous performance analysis of optical CDMA (OCDMA) systems is presented for three different structures. These structures are on-off orthogonal (OOO), on-off orthogonal with single optical hard limiter (OOO-SHL) and on-off orthogonal with double optical hard limiters (OOO-DHL). For each of the above schemes two types of receiver structures is evaluated. The performance is analyzed under the Gaussian approximation for an avalanche photodiode (APD) output where the effect of APD noise, thermal noise and interference are included. Also, the numerical results have been plotted.**

I. INTRODUCTION

The performance analysis of incoherent and asynchronous on-off orthogonal (OOO) and on-off orthogonal with single optical hard limiter (OOO-SHL) using optical orthogonal codes (OOCs) has been done by Kwon [1]. In this paper, we report some new results of analyzing OOO and OOO-SHL Optical CDMA (OCDMA) systems. We also analyze on-off orthogonal with double optical hard limiters (OOO-DHL) OCDMA systems.

In our analysis distractive factors, such as multiple access interference (MAI) and thermal noise are considered. For coding process we have used optical orthogonal codes (OOCs).
The numerical results of our analysis for two types of receiver structures have been presented. In both types, we have used APD as photo detector.

In section II, we introduce the model of system we have used. In sections III, IV and V we analyze the performance of OOO, OOO-SHL and OOO-DHL OCDMA systems, respectively. Finally, we show our numerical results in section VI and at the end we conclude our work.

II. SYSTEM MODEL

Fig. 1 shows the system model which is used for analyzing OOO OCDMA systems. As shown, data bits drive a pulsed laser. If the input bit is “0”, laser will not be excited and no pulse will be created. If the data bit is “1”, the laser will be excited and a narrow laser pulse will be generated. This pulse is fed to an optical encoder which creates a unique code for that subscriber. This signal is given to an N×N passive star coupler (PSC) of a local area network (LAN).

In the receiver side, a mixed signal of different users is obtained. This signal is guided to an optical decoder and then to a part we have called it PISC. The PISC includes photo detection, integrate and dump, sampling and comparison with threshold level. Finally, the estimated sent bit will be detected.

The signal sent by each user can be modeled as [1]

$$S_n(t) = Ib_n(t)C_n(t), \quad n = 1,2,...,N \quad 0 \le t \le FT_c \tag{1}$$

where I shows the intensity of each “mark” in the related weight positions and $b_n(t)$ shows the bit stream of n-th user. Also, $C_n(t)$ shows the code sequence of that user.

Considering asynchronous OCDMA systems, the input signal to the receiver is [1]

$$r(t) = \sum_{n=1}^{N} S_n(t - \tau_n) \tag{2}$$

where τ_n is the n-th user’s delay with respect to the first user as reference.

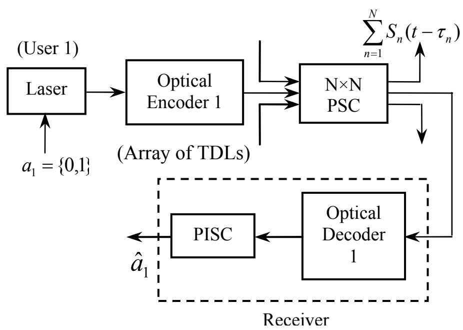

Fig. 1 The model of OOO OCDMA systems.

Regarding the encoder, we can have two types of receiver structures. If we use an optical code multiplier in the transmitter side, we should use the same multiplier at the receiver. We call the receiver that uses this type of encoder "type I". If an array of tapped delay line (TDL) is used as the encoder, we will use another TDL which is inversely matched to the first one in the receiver side and we call it "receiver of type II". We will perform our analysis based on these two types of receiver structures. A comparison between different types of fiber optic CDMA receivers is presented in [2]. Figs. 2 and 3 show the receiver structures of types I and II, respectively.

The probability that a specific number of photons are absorbed by an APD over a chip duration interval (T_c) is given by a Poisson distribution. The average number of absorbed photons is $\lambda_s T_c$, where λ_s represents the photon absorption rate due to a mark transmission in the desired user sequence which can be written as [1]

$$\lambda_s = \eta P_R / (h\upsilon) \tag{3}$$

where P_R is the received laser power, η is the APD efficiency in converting incident photons to photoelectrons, h is the Plank's constant and υ is the optical frequency.

In practice, when a laser is modulated with "0", its output will not be zero, but it will be equal to a fraction of the laser output corresponding to "1". This fraction is called "modulation extinction ratio" and shown by M_e. So, we have

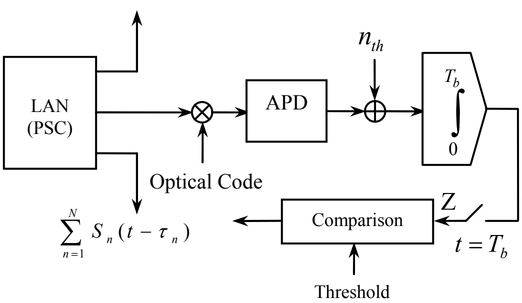

Fig. 2 The receiver structure of type I [2].

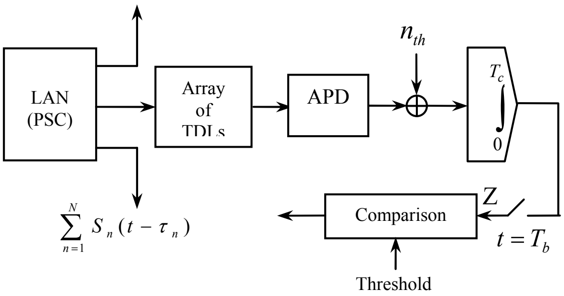

Fig. 3 The receiver structure of type II [2].

$$\lambda_{TOTAL} = \begin{cases} \lambda_S & if\ bit = "1" \\ \lambda_S / M_e & if\ bit = "0" \end{cases} . \tag{4}$$

In the model of APD, there are two internal currents namely "bulk leakage current" and "surface leakage current" shown by I_b and I_s. These current sources are modeled in front of and behind the stochastic gain block, respectively.

As shown in Figs. 1 and 2, the output of sampler is the decision making variable Z. Considering receiver of type I, we have [1]

$$Z = \int_0^{T_b} APD\{r(t) \cdot C_1(t)\} dt \tag{5}$$

where APD{x(t)} is the output signal of the APD to the input x(t), $r(t)$ is the received signal to decoder and $C_1(t)$ is the code sequence of first user (desired user). Before analyzing the above equation, interference is briefly described.

A. *Interference*

From the mark interference point of view, the sequence generated by each undesired user could have three different cases listed below:

Case 1: In this case, which we call it "strong interference", the codes of desired and undesired users overlap at one mark position, and the bit transmitted by the undesired user is "1".

Case 2: In this case, which we call it "weak interference", the codes of desired and undesired users overlap at one mark position, but the bit transmitted by the undesired user is "0". Because of the modulation extinction ratio, there will be some interference in this case.

Case 3: Another possibility is that the codes of undesired and desired users do not have common mark. This situation is the best from interference point of view, since there will be no interference.

Let i_j^s (i_j^w) be the number of users that their code sequences have strong interference (weak interference) with the *j*-th mark of desired user code. We define

$$I^S = \sum_{j=1}^{K} i_j^s \tag{6}$$

$$I^W = \sum_{j=1}^{K} i_j^w \tag{7}$$

where K is the weight of each code (number of marks in the code sequence). It should be noted that it is impossible to have both strong and weak interferences in a bit duration (T_b). In other words, the summation of I^S and I^W never exceeds N-1, where N is the total number of users in the network.

Considering the receiver structures of type I and II, the statistics of Z depends on the K number of T_c intervals corresponding to the mark positions that go through APD.

Fig. 4 shows an example of interference on the desired user's sequence. In this example, there are totally five users, the first four are sending "1" and the last one is sending "0". For simplicity, OOC and asynchronicity is not considered in this figure. It is clear from the above example that optical multiplier blocks all space positions in the desired code.

Fig. 5 shows similar example for a receiver of type II. It should be noted that in this case, only the last chip interval of TDL signals is needed for decision making variable Z. Therefore, other chip intervals are not shown in parts c-f.

For analyzing Z, we break the integral into F chip intervals. The random variables over each chip interval of $C_1(t)$ are independent [1]. We, therefore, have

$$Z = \sum_{j=1}^{K} X_j^{mark} + \sum_{i=1}^{F-K} X_i^{space} \tag{8}$$

where X_j^{mark} (X_j^{space}) is the random variable corresponding to the *j*-th mark (space) position of received sequence by APD. The random variable Z is sum of F independent Gaussian random variables.

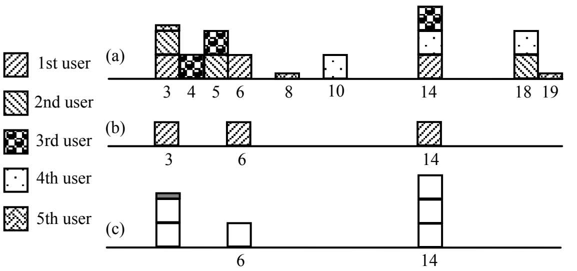

Fig. 4 An example of interference for receiver of type I: (a) received signal, (b) desired code, (c) output of optical multiplier.

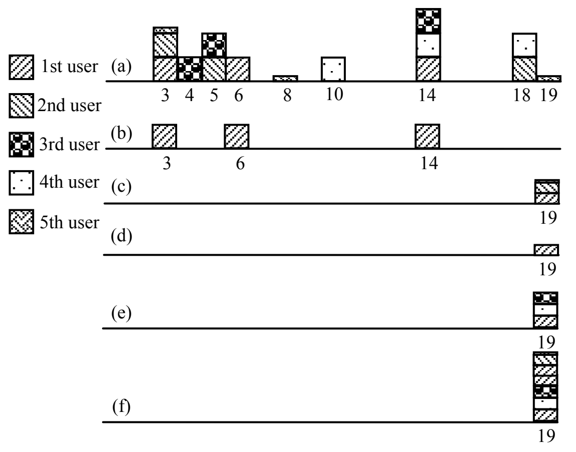

Fig. 5 An example of interference for the receiver of type II: (a) received signal, (b) desired code, (c) output signal of first output of TDL, (d) output signal of second output of TDL, (e) output signal of third output of TDL, (f) signal that goes through APD.

III. Bit Error Rate of OOO Systems

To obtain the bit error rate in OOO OCDMA systems, we need to have the probability density function of I^S, i.e. $P_{I^S}(i)$, and the conditional probability of $I^W \middle| I^S$, i.e. $P_{I^W|I^S}(j|i)$. The probability of interference between two codes that each of them has a weight of K and a length of F is K^2/F [3]. If we assume equal probability for both "0" and "1" bits, the probability of strong and weak interference between two codes would be $K^2/2F$. We have

$$P_{I^S}(i) = \binom{N-1}{i}\left(\frac{K^2}{2F}\right)^i\left(1-\frac{K^2}{2F}\right)^{N-1-i}, \quad i = 0,1,\ldots,N-1 \tag{9}$$

$$P_{I^W|I^S}(j\,|\,i) = \binom{N-1-i}{j}\left(\frac{K^2}{2F}\right)^j\left(1-\frac{K^2}{2F}\right)^{N-1-i-j} \cdot \quad i = 0,1,\ldots,N-1 \quad j = 0,1,\ldots,N-1-i \tag{10}$$

Assuming the transmitted bit of the desired user being "1", and the strong and weak interferences are known, the conditional probability density function of the Gaussian random variable Z in the receiver of type I is

$$P_Z(Z\,|\,I^S, I^W, b = "1") = \frac{1}{\sqrt{2\pi\sigma_1^2}}\exp\left\{\frac{-(Z-\mu_1)^2}{2\sigma_1^2}\right\} \tag{11}$$

where μ_1 and σ_1^2 are the mean and variance of random variable Z, respectively. These parameters can be obtained using the following equations

$${}^{I}\mu_1 = GT_c\left[(K+I^S)\lambda_s + I^W\frac{\lambda_s}{M_e} + F\frac{I_b}{e}\right] + FT_c\frac{I_s}{e} \tag{12}$$

$${}^{I}\sigma_1^2 = G^2F_e\left[\left(K+I^S\right)\lambda_s + I^W\frac{\lambda_s}{M_e} + F\frac{I_b}{e}\right] + F\left(T_c\frac{I_s}{e} + \sigma_{th}^2\right) \tag{13}$$

where the upper index, indicates the type of receiver. G is the mean value of random gain of APD and e is the charge of an electron. Also, F_e is the excess noise factor defined as

$$F_e = \kappa_{eff}G + \left(2-\frac{1}{G}\right)\left(1-\kappa_{eff}\right) \tag{14}$$

where κ_{eff} is the effective ionization ratio and its value depends on the wavelength and material used for photo detector. This value is much smaller than 1 for silicon at the wavelength of 800nm and is about 0.7 for InGaAs at the wavelengths of 1300nm and 1500nm [4].

Also, in Eq. (13), σ_{th}^2 is thermal noise variance of APD and its value is related to the system parameters as

$$\sigma_{th}^2 = \frac{2k_B T_r T_c}{e^2 R_L} \quad (15)$$

where $k_B = 1.3793\times10^{-23}$ Joule/°K is the Blotzmann constant, T_r is the receiver noise temperature, and R_L is the receiver load resistor.
Table I shows the typical values of an OCDMA system using APD.

We continue the same procedure for finding conditional pdf of Z when the transmitted bit is 0. We have

$$P_Z(Z \mid I^S, I^W, b = "0") = \frac{1}{\sqrt{2\pi\sigma_0^2}}\exp\left\{\frac{-(Z-\mu_0)^2}{2\sigma_0^2}\right\} \quad (16)$$

Again, we define some new parameters

$$^I\mu_0 = GT_c\left[I^S\lambda_s + I^W\frac{\lambda_s}{M_e} + F\frac{I_b}{e}\right] + FT_c\frac{I_s}{e} \quad (17)$$

$$^I\sigma_0^2 = G^2F_e\left[I^S\lambda_s + I^W\frac{\lambda_s}{M_e} + F\frac{I_b}{e}\right] + F\left(T_c\frac{I_s}{e} + \sigma_{th}^2\right) \quad (18)$$

Having conditional probability of error, we can find the probability of error in OOO OCDMA systems

$$P_b(Error) = \min_{Th}\left\{E_{I^S, I^W, b}\left\{P_b(Error \mid I^S, I^W, b, Th)\right\}\right\} \quad (19)$$

where $E_y\{x\}$ indicates the expected value of x with respect to y. Using the above equation, we will have

$$P_b(Error) = \min_{Th}\frac{1}{2}\{\ 1 + \sum_{i=0}^{N-1}\sum_{j=0}^{N-1-i}P_{I^S}(i)P_{I^W|I^S}(j \mid i) \times\left[Q\left(\frac{Th-\mu_0(i,j)}{\sigma_0(i,j)}\right) - Q\left(\frac{Th-\mu_1(i,j)}{\sigma_1(i,j)}\right)\right]\} \quad (20)$$

where Q in the above equation represents the Q function [5]. Using similar procedure for the receiver of type II, we will obtain the same result as Eq. 20 replacing the parameters as below

$$^{II}\mu_1 = GT_c\left[\left(\frac{K+I^S}{K}\right)\lambda_s + \frac{I^W}{K}.\frac{\lambda_s}{M_e} + \frac{I_b}{e}\right] + T_c\frac{I_s}{e} \quad (21)$$

$$^{II}\sigma_1^2 = G^2F_eT_c\left[\left(\frac{K+I^S}{K}\right)\lambda_s + \frac{I^W}{K}.\frac{\lambda_s}{M_e} + \frac{I_b}{e}\right] + T_c\frac{I_s}{e} + \sigma_{th}^2 \quad (22)$$

$$^{II}\mu_0 = GT_c\left[\frac{I^S}{K}\lambda_s + \frac{I^W}{K}.\frac{\lambda_s}{M_e} + \frac{I_b}{e}\right] + T_c\frac{I_s}{e} \quad (23)$$

$$^{II}\sigma_0^2 = G^2F_eT_c\left[\frac{I^S}{K}\lambda_s + \frac{I^W}{K}.\frac{\lambda_s}{M_e} + \frac{I_b}{e}\right] + T_c\frac{I_s}{e} + \sigma_{th}^2 \quad (24)$$

TABLE I
TYPICAL VALUES OF AN OCDMA SYSTEM USING APD [1]

Parameter	Symbol	Value
Laser frequency	υ	2.424×10^{14} Hz
Quantum efficiency	η	0.6
APD mean gain	G	100
Effective ionization ratio of APD	κ_{eff}	0.02
Bulk leakage current	I_b	0.1 nA
Surface leakage current	I_s	10 nA
Modulation extinction ratio	M_e	100
Receiver noise temperature	T_r	1100°K
Receiver load resistance	R_L	1030 Ω

IV. BIT ERROR RATE OF OOO-SHL SYSTEMS

A major disadvantage of OOO systems is their weakness to interference. Salehi *et al.* have proposed using a single hard limiter in the receiver to improve the performance of OCDMA systems to interference [6]. This ensures that in each chip position, the received optical power to the detection part does not exceed the power generated at transmitter. Hard limiter is a nonlinear optical device modeled as

$$HL\{x\} = \begin{cases} 1, & x \ge 1 \\ 0, & 0 \le x < 1 \end{cases} \quad (25)$$

where x is the optical power at the receiver for every chip interval. The model used for the analysis of OOO-SHL OCDMA systems is like the one used for OOO systems, i.e. just adding a hard limiter behind the optical decoder. The performance of OOO-SHL OCDMA systems depends on the number of nonzero elements of interference vector [1], [7].

Regarding the typical values selected for code length (F) that are about 1000 and nominal code weights that is less than 10, the maximum number of simultaneous users in such LAN is decreased to the range of 10 to 50. Considering these practical points has the benefit of decreasing the complexity of analysis of OOO-SHL OCDMA systems.

It can be shown that if the number of users in LAN does not exceed M_e, the weak interference effect on the performance of OOO-SHL systems will be negligible. It is clear that this result does not depend on the receiver structure because this is the direct result of using hard limiter at the receiver.

Considering the weak interference case in the analysis of OOO-SHL OCDMA systems we have

$$P_b(Error | b = "0", Th) = Q\left(\frac{Th-\mu_0}{\sigma_0}\right)P_{I^S}(0) + \sum_{i=1}^{N-1}\sum_{m=1}^{\min(K,i)}Q\left(\frac{Th-\mu_0(m)}{\sigma_0(m)}\right) \times \Pr(|\underline{i}^S| = m | I^S = i)P_{I^S}(i) \quad (26)$$

where depending on the receiver type, the parameters are

$$^{I}\mu_0 = GT_cFI_b/e + FT_cI_s/e \quad (27)$$

$$^{I}\sigma_0^2 = G^2F_eT_cFI_b/e + F(T_cI_s/e + \sigma_{th}^2) \quad (28)$$

$$^{II}\mu_0 = GT_cI_b/e + T_cI_s/e \quad (29)$$

$$^{II}\sigma_0^2 = G^2F_eT_cI_b/e + T_cI_s/e + \sigma_{th}^2 \quad (30)$$

$$^{I}\mu_0(m) = GT_c[m\lambda_s + FI_b/e] + FT_cI_s/e \quad (31)$$

$$^{I}\sigma_0^2(m) = G^2F_eT_c[m\lambda_s + FI_b/e] + F(T_cI_s/e + \sigma_{th}^2) \quad (32)$$

$$^{II}\mu_0(m) = GT_c\left[\frac{m}{K}\lambda_s + \frac{I_b}{e}\right] + T_cI_s/e \quad (33)$$

$$^{II}\sigma_0^2(m) = G^2F_eT_c\left[\frac{m}{K}\lambda_s + \frac{I_b}{e}\right] + T_cI_s/e + \sigma_{th}^2 \quad (34)$$

Assuming the transmitted bit is "1" and the threshold value is known, the probability of error is

$$P_b(Error \mid b = "1", Th) = \sum_{i=0}^{N-1} \Pr(Z < Th \mid I^S = i, b = "1", Th) \times P_{I^S}(i) = \sum_{i=0}^{N-1}\left[1 - Q\left(\frac{Th - \mu_1}{\sigma_1}\right)\right]P_{I^S}(i) = 1 - Q\left(\frac{Th - \mu_1}{\sigma_1}\right) \quad (35)$$

where depending on the receiver type, the parameters are

$$^{I}\mu_1 = GT_c[K\lambda_s + FI_b/e] + FT_cI_s/e \quad (36)$$

$$^{I}\sigma_1^2 = G^2F_eT_c[K\lambda_s + FI_b/e] + F(T_cI_s/e + \sigma_{th}^2) \quad (37)$$

$$^{II}\mu_1 = GT_c[\lambda_s + I_b/e] + T_cI_s/e \quad (38)$$

$$^{II}\sigma_1^2 = G^2F_eT_c[\lambda_s + I_b/e] + T_cI_s/e + \sigma_{th}^2 \quad (39)$$

Having $P_b(Error \mid b = "0", Th)$, $P_b(Error \mid b = "1", Th)$ and assuming equal probability of transmitting "1" and "0", the optimum value of the bit error rate is derived

$$P_b = \min_{Th} \frac{1}{2}\{P_b(Error \mid b = "0", Th) + P_b(Error \mid b = "1", Th)\} \quad (40)$$

V. Bit Error Rate of OOO-DHL Systems

Ohtsuki *et al.* introduced the idea of using double hard limiters (DHL) in synchronous OCDMA systems [8] and, later, extended this idea to asynchronous systems [9]. They used Poisson approximation for APD in their analysis. In this section, we do similar analysis using Gaussian approximation for APD.

The system model used is similar to the one shown in Fig. 1, except that we add two hard limiters at both sides of decoder for both types of receivers.

The ability of interference cancellation of OOO-DHL OCDMA systems is high because they can cancel all interference patterns except those that have vector amplitude equal to the weight of code. In other words, in these systems, a bit error happens when a "0" is transmitted by the desired user and interference occurs at all mark positions.

Since the main factor that affects the performance of such OCDMA systems is the interference of other users, it is expected that the performance of OOO-DHL OCDMA systems be better than OOO-SHL systems and the later be better than OOO OCDMA systems.

As in OOO-SHL systems, we assume the number of users is less than M_e. We, therefore, have

$$P_Z(z \mid I^S, b = "1") = \frac{1}{\sqrt{2\pi\sigma_1^2}} \exp\left\{\frac{-(z - \mu_1)^2}{2\sigma_1^2}\right\} \quad (41)$$

$$P_Z(z \mid I^S, b = "0", |\underline{i}^S| = K) = \frac{1}{\sqrt{2\pi\sigma_{0(pass)}^2}} \times \exp\left\{\frac{-(z - \mu_{0(pass)})^2}{2\sigma_{0(pass)}^2}\right\} \quad (42)$$

$$P_Z(z \mid I^S, b = "0", |\underline{i}^S| < K) = \frac{1}{\sqrt{2\pi\sigma_{0(block)}^2}} \times \exp\left\{\frac{-(z - \mu_{0(block)})^2}{2\sigma_{0(block)}^2}\right\} \quad (43)$$

Depending on the receiver type, the values of mean and variance in the above equations are

$$^{I}\mu_{0(pass)} = {}^{I}\mu_1 = GT_c[K\lambda_s + FI_b/e] + FT_cI_s/e \quad (44)$$

$$^{I}\sigma_{0(pass)}^2 = {}^{I}\sigma_1^2 = G^2F_eT_c[K\lambda_s + FI_b/e] + F(T_cI_s/e + \sigma_{th}^2) \quad (45)$$

$$^{I}\mu_{0(block)} = GT_cFI_b/e + FT_cI_s/e \quad (46)$$

$$^{I}\sigma_{0(block)}^2 = G^2F_eT_cFI_b/e + F(T_cI_s/e + \sigma_{th}^2) \quad (47)$$

$$^{II}\mu_{0(pass)} = {}^{II}\mu_1 = GT_c[\lambda_s + I_b/e] + T_cI_s/e \quad (48)$$

$$
{}^{II}\sigma^2_{0(pass)} = {}^{II}\sigma_1^2 = G^2 F_e T_c[\lambda_s + I_b / e] + T_c I_s / e + \sigma_{th}^2 \quad (49)
$$

$$
{}^{II}\mu_{0(block)} = G T_c I_b / e + T_c I_s / e \quad (50)
$$

$$
{}^{II}\sigma^2_{0(block)} = G^2 F_e T_c I_b / e + T_c I_s / e + \sigma_{th}^2 \quad (51)
$$

The bit error rate of OOO-DHL OCDMA systems can be calculated as follows

$$
\begin{aligned}
P_b(Error|b=\text{"0"},Th) &= \sum_{i=K}^{N-1} Q\left(\frac{Th-\mu_{0(pass)}}{\sigma_{0(pass)}}\right) \\
&\times \Pr(|\underline{i}^S| = K | I^S = i) P_{I^S}(i) \\
&+ \sum_{i=1}^{N-1} \sum_{m=1}^{\min(i,K-1)} Q\left(\frac{Th-\mu_{0(block)}}{\sigma_{0(block)}}\right) \times \Pr(|\underline{i}^S| = m | I^S = i) \\
&\times P_{I^S}(i) + Q\left(\frac{Th-\mu_{0(block)}}{\sigma_{0(block)}}\right) P_{I^S}(0)
\end{aligned} \quad (52)
$$

$$
\begin{aligned}
P_b(Error | b=\text{"1"},Th) &= \sum_{i=0}^{N-1} \Pr(Z < Th | I^S = i, b=\text{"1"},Th) \\
\times P_{I^S}(i) &= \sum_{i=0}^{N-1} \left[1 - Q\left(\frac{Th-\mu_1}{\sigma_1}\right)\right] P_{I^S}(i) \\
&= 1 - Q\left(\frac{Th-\mu_1}{\sigma_1}\right)
\end{aligned} \quad (53)
$$

Using these values, the probability of error can be calculated from Eq. (40).

VI. Numerical Results

Considering the large value of modulation extinction ratio and reminding that λ_s / M_e in the obtained results is I^W, we neglect I^W as an approximation to our rigorously derived equations. Replacing $I^W = 0$ for both receiver types, we obtain approximated results. This results in the elimination of Eq. (10). Also, Eq. (19) will be changed to

$$
P_b(Error) = \min_{Th}\{E_{I^S,b}\{P_b(Error | I^S, b, Th)\}\} \quad (54)
$$

Similarly, Eq. (20) we will be changed to

$$
E_{I^S,b}\{P_b(Error|I^S,b,Th)\} = \frac{1}{2}\left\{1 + \sum_{i=0}^{N-1} P_{I^S}(i)\left[Q\left(\frac{Th-\mu_0(i)}{\sigma_0(i)}\right) - Q\left(\frac{Th-\mu_1(i)}{\sigma_1(i)}\right)\right]\right\}. \quad (55)
$$

Using the typical values listed in Table I, the numerical results show that this approximation is acceptable. From here on, "received laser power" (P_w) means received optical power from the desired user in a chip interval corresponding to mark position in the received sequence assuming that the transmitted bit is "1". If the transmitted bit is "0", the received power would be P_w / M_e.

As the numerical results demonstrate receiver of type I performs better than type II. Therefore, we just plot its results in this section. In this part, we will consider the effect of increasing the number of users (N) and code weight (K) in OOO, OOO-SHL and OOO-DHL OCDMA. We have summarized these effects in Figs. 6-11.

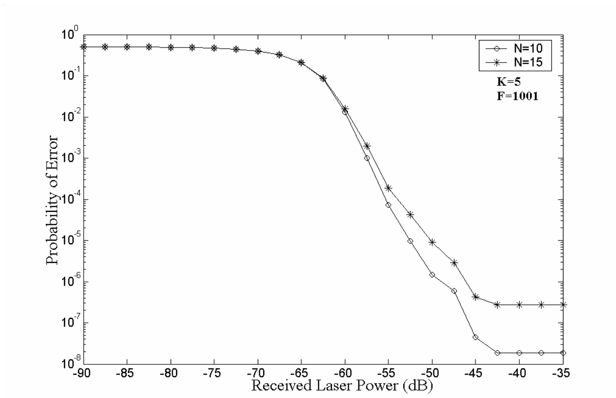

Fig. 6 The effect of increasing simultaneous users on the performance of OOO OCDMA systems.

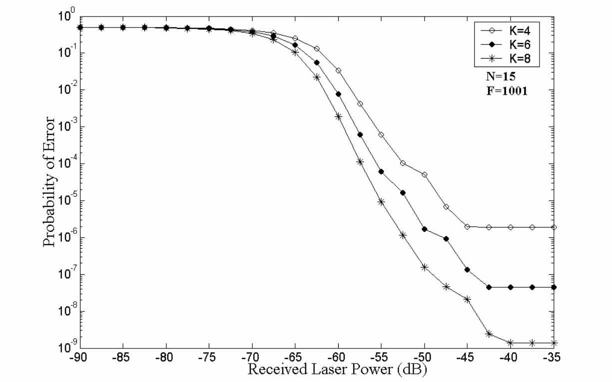

Fig. 7 The effect of increasing the weight of codes on the performance of OOO OCDMA systems.

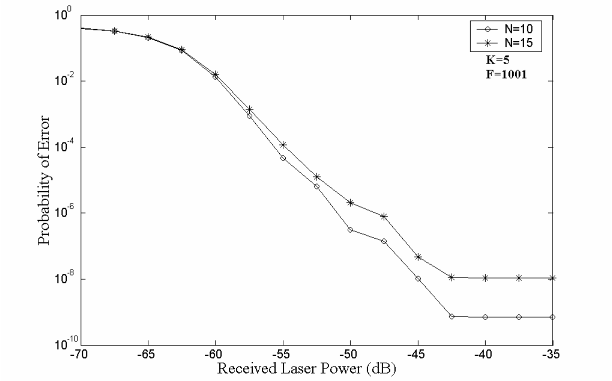

Fig. 8 The effect of increasing simultaneous users on the performance of OOO-SHL OCDMA systems.

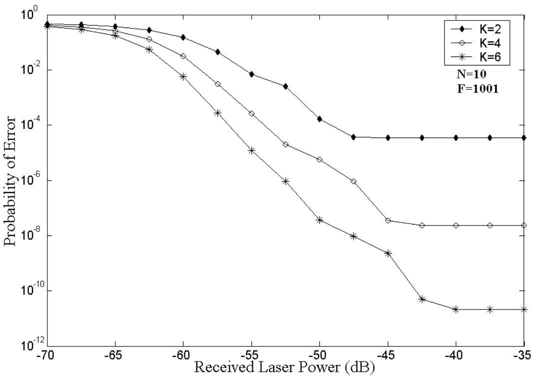

Fig. 9 The effect of increasing the weight of codes on the performance of OOO-SHL OCDMA systems.

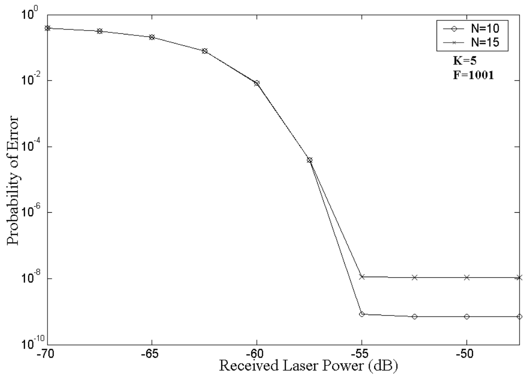

Fig. 10 The effect of increasing simultaneous users on the performance of OOO-DHL OCDMA systems.

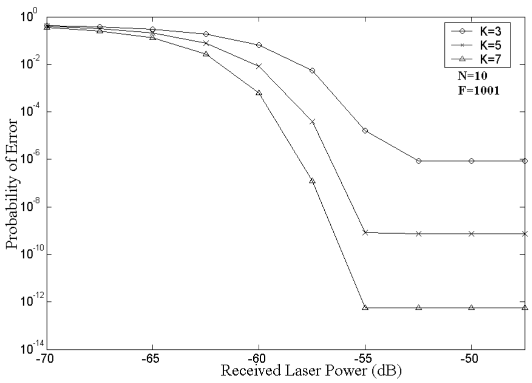

Fig. 11 The effect of increasing the weight of codes on the performance of OOO-DHL OCDMA systems.

Conclusions

In this paper, we analyzed three types of OOO OCDMA systems, i.e. OOO, OOO-SHL and OOO-DHL systems. We chose two types of receiver structures and analyzed the performance of the above systems for both receivers. Our results showed that the receiver of type I performs better than type II. Choosing receiver of type I, we presented our numerical results. Also, we demonstrated the effect of increasing the number of users and code weight on the performance of these systems. Our results showed that OOO-DHL OCDMA systems are better than the others. The reason is that using double hard limiters results in removing many possible interference patterns.

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