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Performance analysis of an optical CDMA system with non-ideal optical hard-limiters

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Abstract

Performance analysis of an incoherent time spread on–off keying optical Code Division Multiple Access (O-CDMA) system with non-ideal optical hard-limiters is reported in this paper. For the first time we made an approximation of the properties of an implemented passive optical hard-limiter. It was named as a non-ideal optical hard-limiter and its non-ideal parameter was defined. Shortened optical orthogonal codes generated by an extended set technique achieved multiple accesses in the investigated O-CDMA system. Performance improvement of O-CDMA system for the cases of O-CDMA receiver without any, with one and with two optical hard-limiters is shown by simulation of the signal-to-interference ratio and the bit error probability. The influence of non-ideal properties of the optical hard-limiter upon the performance of O-CDMA system is studied.

PACS: 42.79.S

Keywords: Optical CDMA; Optical communication; Passive optical hard-limiter

1. Introduction

Optical code division multiple access systems are modern schemes for fiber-optic networks, which allow asynchronous transmission mode and accession to the optical network simultaneously. The block diagram of O-CDMA system topology is shown in Fig. 1. All user signals are distributed to all users by the star topology of the optical network. In incoherent time spread O-CDMA systems, a specific binary codeword is assigned to each user. If the user is transmitting the data bit "One", then its transmitter sends a codeword to the network, otherwise no signal is sent. Each user's O-CDMA decoder is matched to its intended signal. The O-CDMA does not contain electrical devices, which are the limiting factors of the bit rate in the current electrical multiple access systems. Thus,

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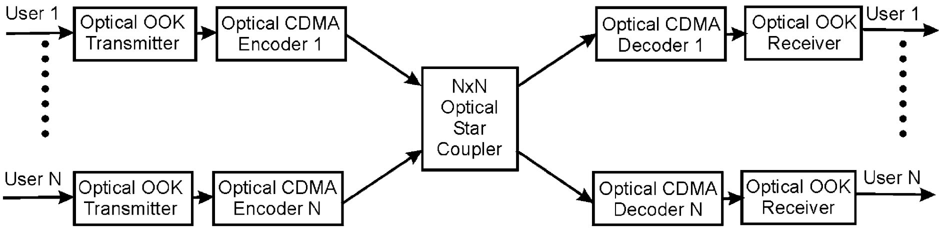

Fig. 1. The block diagram of CDMA network topology.

O-CDMA systems are promising for future ultra-high-speed communication systems.

One of the most important problems for O-CDMA systems is the multiple-access interference (MAI), which limits the number of active users in the system. Fig. 2 shows the block diagram of the proposed O-CDMA decoder and the optical OOK receiver. The function of O-CDMA decoder is to select the desired user's signal from the received signal, which is a sum of all active users' transmitted codewords. One possible way to reduce the degradation due to MAI is to use optical hard-limiters placed before and after the optical correlator and referred to as the first and second optical hard-limiters (HL) [2–4]. The optical HL is a nonlinear optical device two valued output optical intensity of which $I_{\mathrm{OUT}}(I_{\mathrm{IN}})$ depends on the optical intensity at the input. The ideal optical HL is defined as [2–4]

$$I_{\mathrm{OUT}}(I_{\mathrm{IN}}) = \begin{cases} 0 & 0 < I_{\mathrm{IN}} \leqslant T_{\mathrm{h}}, \\ v_{\mathrm{f}} & I_{\mathrm{IN}} > T_{\mathrm{h}}, \end{cases} \qquad (1)$$

where v_{f} is a fixed value of the optical intensity depending on the input optical intensity and T_{h} is the threshold level of the optical HL. The first optical HL (HL1) sets the amplitudes of the incoming optical pulses to an equal value. The passive optical correlator performs the correlation function of the sequence of the incoming optical chip pulses. Possible realizations of an optical correlator for the time spread O-CDMA system are presented in [1]. If the desired user transmitted data bit is "One", an autocorrelation optical chip pulse will appear at the output of the optical correlator with energy that is w-times the energy of each incoming optical chip pulse. The second optical HL (HL2) selects the autocorrelation optical chip pulse from the output optical chip pulses of the optical correlator. At the end an optical OOK receiver detects the "One" or "Zero" data bit, respectively.

Performance analyses of O-CDMA systems with various O-CDMA receiver topologies were the subject of many papers [2–5]. Salehi and Brackett [2] analyzed the channel interference of O-CDMA system and they have shown an improvement in system performance by the using of the optical HLs in O-CDMA decoder. However, their analysis was assuming only MAI. Authors in [3,4] have analyzed the performance of O-CDMA system with and without the optical HLs and they have assumed the Poisson shot-noise model of photodiodes of the optical OOK receiver. Zahedi and Salehi [5] have studied the performance of O-CDMA systems using various receiver topologies. They have shown that another important factor in the effectiveness of different receiver topologies is the integration time of optical OOK receiver. Their analysis has reported that shorter integration times give better performance results.

All these performance analyses of O-CDMA system have used the ideal optical HL (1), but realization of such an optical HL is not possible. Unlike previous performance analyses, this

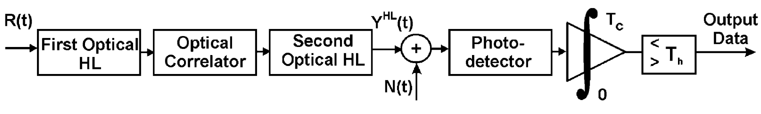

Fig. 2. The block diagram of proposed O-CDMA decoder and optical OOK receiver.

analysis assumes a passive optical HL as proposed and realized by Brzozowski and Sargent [6]. The realized passive optical HL is a periodic structure consisting of alternating layers of materials possessing different optical Kerr nonlinearity [6]. This realized passive optical HL has different properties than the ideal optical HL. This type of a "non-ideal optical HL" is used in this performance analysis of the O-CDMA system. In this paper we approximate the "non-ideal optical HL" properties and we analyze the influence of its non-ideal properties upon the performance of O-CDMA system. In this analysis we assume the Poisson shot-noise model of photodetector of the optical OOK receiver.

The realized optical HL has three regimes of operation as shown in Fig. 3: at low input optical intensities, the input optical signal is resonantly reflected; for intermediate input optical intensity, the system goes through a region of constant differential transmittance; for high input optical intensity, the transmittance redescends to zero. We define a "non-ideal parameter" *NP* of an optical HL, which can assume values from interval (0, 1). For a given choice of *NP*, the output optical intensity $I_{\mathrm{OUT}}(I_{\mathrm{IN}})$ is related to input optical intensity I_{IN} of the optical HL signal by the approximate piece-wise-linear relation:

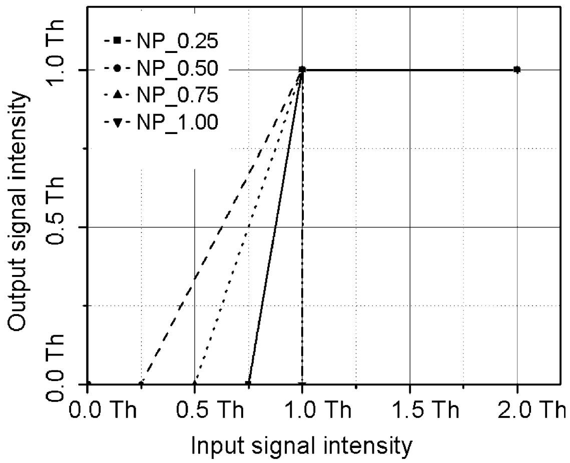

Fig. 3. The input versus output signal intensity of the non-ideal HL for different value of NP.

$$I_{\mathrm{OUT}}(I_{\mathrm{IN}}) = \begin{cases} 0.01 \times I_{\mathrm{IN}}, & I_{\mathrm{IN}} \leqslant T_{\mathrm{h}} \times NP \\ \frac{0.01 \times NP - 1}{NP - 1} \times I_{\mathrm{IN}} + \frac{NP \times (T_{\mathrm{h}} - 0.01 \times T_{\mathrm{h}})}{NP - 1}, & T_h \times NP < I_{\mathrm{IN}} \leqslant T_{\mathrm{h}}, \\ 0.01 \times I_{\mathrm{IN}} + 0.99 \times T_{\mathrm{h}}, & I_{\mathrm{IN}} > T_{\mathrm{h}} \end{cases} \tag{2}$$

where I_{IN} is its input optical intensity, I_{OUT} is its output optical intensity and T_{h} is the threshold level of the optical HL.

2. System model

We consider an incoherent time spread on–off keying O-CDMA system with N transmitter and receiver pairs. N users share the same optical medium usually, but not exclusively, in a star topology. Each kth user's information bit form is encoded into a codeword

$$C_k(t) = \sum_{i=1}^{n} w\lambda_{\mathrm{S}} c_k[i] p_i(t - iT_{\mathrm{C}}), \tag{3}$$

where n is the length of the codeword, $T = nT_{\mathrm{C}}$ is the time duration of data bit and $c_k[i] \in \{0, 1\}$, for $1 \leqslant i \leqslant n$, is the ith chip pulse of the kth user's codeword. Let $C_k = \{c_k[1], c_k[2], \ldots, c_k[n]\}$ be a vector representing the discrete form of the codewords. Further, the chip signaling waveform $p_i(t)$, for $1 \leqslant i \leqslant n$, is assumed to be a unit-amplitude rectangular pulse of the chip time duration T_{C} and $w\lambda_{\mathrm{S}}$ is the signal photon rate at the output of the optical encoder. Each user transmitter broadcasts its encoded signal to all the receivers in the system. The received signal is a sum of all active N users' transmitted signals

$$R(t) = \sum_{k=1}^{N} b_k C_k(t - \tau_k), \tag{4}$$

where $b_k \in \{0, 1\}$ is the kth user's information bit and $0 \leqslant \tau_k \leqslant T$ is the time delay for $k = 1, \ldots, N$. If the decoder applies the first optical HL, then the input signal of the optical correlator can be expressed as

$$R^{\mathrm{HL1}}(t) = I_{\mathrm{HL1}}(R(t)). \tag{5}$$

The optical correlator performs the correlation function of the sequence of incoming optical chip pulses. The output signal of desired kth user's optical correlator is thus

$$S_k(t) = C_k(t) R^{\mathrm{HL1}}(t). \tag{6}$$

If the second optical HL is applied to the output signal of optical correlator, then the output signal of the optical decoder can be express as

$$S_k^{\mathrm{HL2}}(t) = I_{\mathrm{HL2}}(S_k(t)). \tag{7}$$

The output signal of kth user O-CDMA decoder is sequence of optical chip pulses with different amplitudes. It can be expressed as

$$S_k^{\mathrm{HL2}}(t) = \sum_{i=1}^{n} a_k^j[i] \lambda_{\mathrm{S}} p_i(t - iT_{\mathrm{C}}), \tag{8}$$

where a_k^j is normalized amplitude of the optical chip pulse of i-chip time. Let $A_k^j = \{a_k^j[1], a_k^j[2], \ldots, a_k^j[n]\}$ be a vector representing the discrete form of the output chip pulse sequence of kth user decoder. $j \in \{0, 1\}$ for $b_k = 0$ and $b_k = 1$ transmitted data bit, respectively. Let

$$a_{k,\max}^0 = \max\{a_k^0[1], a_k^0[2], \ldots, a_k^0[n]\}, \tag{9}$$

$$a_{k,\max}^1 = \max\{a_k^1[1], a_k^1[2], \ldots, a_k^1[n]\}. \tag{10}$$

This paper uses the average signal-to-interference ratio (SIR) defined as

$$\mathrm{SIR} = \frac{1}{N} \sum_{k=1}^{N} \frac{a_{k,\max}^1}{a_{k,\max}^0}. \tag{11}$$

Under the assumption of the Poisson shot-noise model of the receiver photodetector, the received photocount after the kth user's optical correlator over chip time can be modeled as a conditional Poisson variable Y^k and can be expressed as [3]

$$Y^k = S^k + I^k + N^k, \tag{12}$$

where S^k is the Poisson photon count due to the desired signal, I^k is the Poisson photon count due to the interference and N^k is the Poisson photon count due to noise. S^k and I^k depend on data bits of the kth user and the mean of sum of S^k and I^k is given as

$$E(S^k + I^k) = \left\langle \begin{array}{ll} \lambda_{\mathrm{S}} a_{k,\max}^1 T_{\mathrm{C}}, & b_k = 1, \\ \lambda_{\mathrm{S}} a_{k,\max}^0 T_{\mathrm{C}}, & b_k = 0. \end{array} \right. \tag{13}$$

The mean of N^k is given by [3]

$$E(N^k) = w \lambda_0 T_{\mathrm{C}}, \tag{14}$$

where λ_0 denotes the noise photon rate.

If Y^k achieves a threshold value of θ, data bit "One" is detected; otherwise data bit "Zero" is detected by the OOK optical receiver.

3. Bit error probability

The mean of the total received photon count over chip time for the kth user can be written as follows:

$$E(Y^k | b_k = 0) = \lambda_{\mathrm{S}} a_{k,\max}^0 T_{\mathrm{C}} + w\lambda_0 T_{\mathrm{C}} = m_0, \tag{15}$$

$$E(Y^k | b_k = 1) = \lambda_{\mathrm{S}} a_{k,\max}^1 T_{\mathrm{C}} + w\lambda_0 T_{\mathrm{C}} = m_1. \tag{16}$$

Then the bit error probability for the kth user can be generally expressed as

$$P_{\mathrm{E}} = \frac{1}{2} \mathtt{Pr}(Y^k \geqslant \theta | b_k = 0) + \frac{1}{2} \mathtt{Pr}(Y^k < \theta | b_k = 1), \tag{17}$$

where

$$\mathtt{Pr}(Y^k \geqslant \theta | b_k = 0) = \sum_{x=\theta}^{\infty} \mathrm{Pois}(x, m_0), \tag{18}$$

$$\mathtt{Pr}(Y^k < \theta | b_k = 1) = \sum_{x=0}^{\theta-1} \mathrm{Pois}(x, m_1). \tag{19}$$

Here, $\mathrm{Pois}(a, b)$ denotes the Poisson probability function

$$\mathrm{Pois}(a, b) = \frac{\mathrm{e}^{-b} b^a}{a!}. \tag{20}$$

4. Numerical results

The investigated O-CDMA system has a number of active users up to 300 and uses the shortened optical orthogonal code $(n, w, 1, 1)$. The first number in brackets, n, is the length of the codewords, the second one, w, is the weight of the codewords, and the third and fourth ones are the auto- and cross-correlation constants of the used codewords. The extended set technique algorithm proposed in [7] generates used shortened OOC in the analyzed O-CDMA system. Input independent parameters of this algorithm are the weight, correlation constants and the requested number of codewords; the output dependent parameter of the algorithm is the length of codewords. Sets of 300, 150, 75 and 38 codewords have been generated for weights of codeword from 2 to 30. Fig. 4 shows the length as a function of the weight of the codewords for the requested number of codewords in the set.

In numerical calculation, the bit rate is assumed to be fixed at R_0. Using R_0, the time duration of data bit is expressed as [3]

$$T = \frac{\log 2}{R_0}. \tag{21}$$

This paper uses the optical HL with the threshold level $T_h = w\lambda_S T_C$ defined by Eq. (2). Note that when optical amplification or optical correlators with power loss are present in the system, the optimum value of the threshold level of the optical HL is no longer obvious. The numerical result is calculated by PC software, which random generates the time delay of the kth user codewords τ_k and calculates the output signal of each user O-CDMA decoder. Then it calculates the average SIR in the O-CDMA system with specified parameters.

Figs. 5–8 show the output signal of the first user O-CDMA decoder with and without optical HL for "One" and "Zero" data bit transmission in the O-CDMA system with 75 active users and (6176,10,1,1) OOC, respectively. It can be seen that, when O-CDMA decoder is without optical HL, the amplitude of the created autocorrelation optical chip pulse does not have the defined amplitude by used OOC and some other optical chip pulses have the comparable amplitude than autocorrelation optical chip pulse.

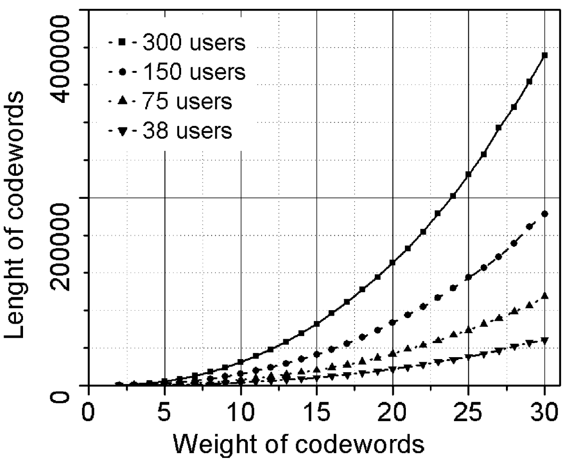

Fig. 4. The length versus weight of the codewords for various numbers of the active users.

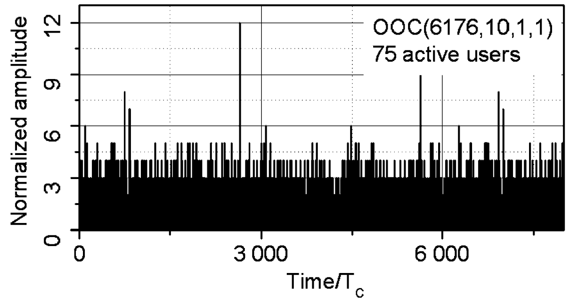

Fig. 5. The output signal of the first user O-CDMA decoder without any optical HL for "One" data bit transmission.

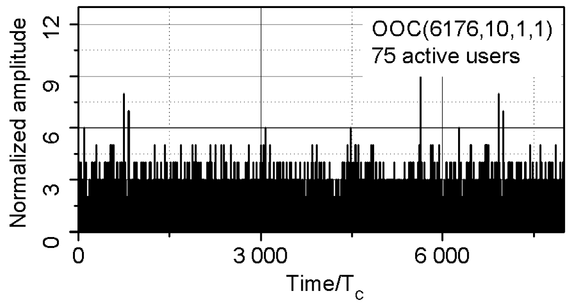

Fig. 6. The output signal of the first user O-CDMA decoder without the optical HL for "Zero" data bit transmission.

The variance of SIR as a function of the weight of the codewords for two cases, thus when the decoder contains only the first optical HL (HL1) and without optical HL (without HL1), is shown in Fig. 9. The SIR achieves values from 1 to less than 5 in these cases. It can be seen that the ratio value of SIR for a decoder without optical HL and with the first optical HL is smaller than one.

The variation of the SIR as a function of the weight of codewords for various numbers of active users in the O-CDMA system (300, 150, 75, 38) is

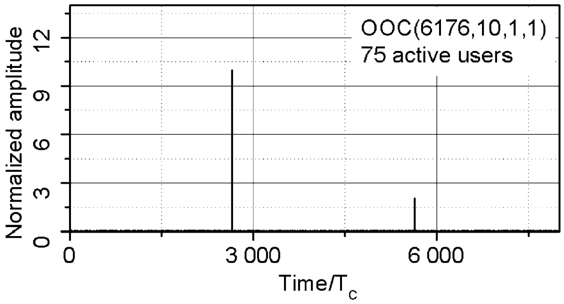

Fig. 7. The output signal of the first user O-CDMA decoder with both the optical HLs for "One" data bit transmission.

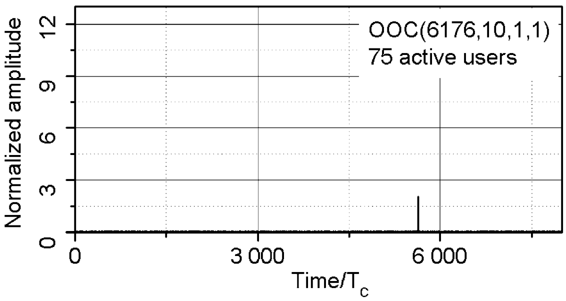

Fig. 8. The output signal of the first user O-CDMA decoder with both the optical HLs for "Zero" data bit transmission.

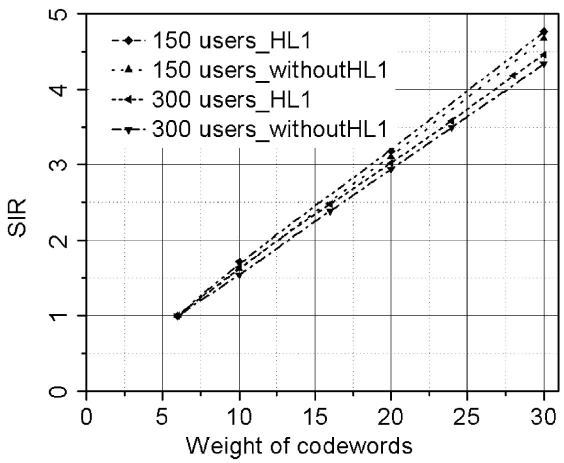

Fig. 9. SIR versus weight of the codewords for the decoder without the optical HL and with the first optical HL.

shown in Fig. 10. This dependence is in the case when the decoder contains both optical HLs. From Fig. 10 we can see that for w varied from 8

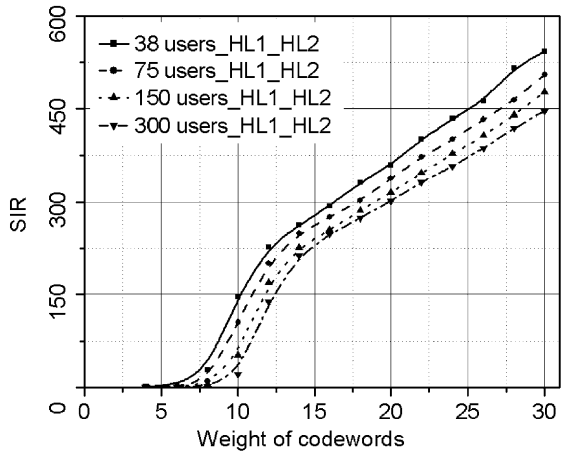

Fig. 10. SIR versus weight of the codewords for various numbers of the active users for the decoder with the both optical HLs.

to 13 the SIR increases more rapidly as the w is varied up to 8 or over 13.

Fig. 11 shows the SIR as a comparison of the function of the weight of codewords for two cases: when the encoder contains only the second optical HL (HL2) and when it contains both optical HLs (HL1_HL2). When the SIR of these cases is compared, case HL1_HL2 shows a better SIR than case HL2. For SIR equal to 200 in the system

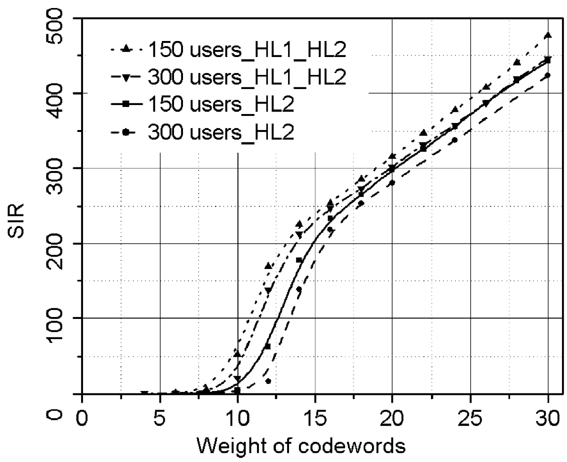

Fig. 11. SIR versus weight of the codeword for various numbers of the active users for the encoder: HL1_HL2 with the both optical HLs, HL2 with only the second optical HL.

with 300 users, in the case of HL2 it is necessary to use the weight of codewords $w = 16$, however, in the case of HL1_HL2 the weight of the codewords $w = 13$ is sufficient.

From Figs. 9–11 we can see that the second HL of the O-CDMA decoder has a prime effect upon the SIR in the system, which changes the value of SIR from 5 to 400.

Fig. 12 shows the variation of SIR as a function of the weight of codewords for six different values of the non-ideal parameter *NP* of the optical HL. The *NP* determines the measure of non-ideal properties of the optical HL. If the value of *NP* converges to 1, then the properties of the non-ideal optical HL converge to the properties of an ideal optical HL. If the value of *NP* is much lower than 1, then the properties of the non-ideal HL are different than the properties of the ideal optical HL. Fig. 12 depicts the effect of non-ideal properties of a non-ideal optical HL in the O-CDMA system on SIR. From the dependence it can be seen that for achieving the same value of SIR (e.g., 150) for different values of *NP* 0.25, 0.3, 0.4, 0.5, 0.75, 0.9, the weight of the codewords has to be equal to about 23, 19, 16, 12, 8, 7.

Fig. 13 shows the SIR as a function of the number of active users in the O-CDMA system for the fixed weight of codewords $w = 10$, the O-CDMA encoder with both optical HLs and for various value of *NP*. For a given value of *w*, as the number of active users increases, SIR decreases from 500 to less than 200. If only two users are present in the system, then the normalized amplitude of the autocorrelation chip pulse is equal to the weight of the codeword and the amplitude of the undesirable chip pulse is equal to the cross-correlation constant of the used shortened OOC. On the contrary, if all 300 users are present in the system, the amplitude of the autocorrelation chip pulse is not changed but the amplitude of the undesirable chip pulse theoretically decreases down to 300 if an optical HL is not present in the O-CDMA decoder.

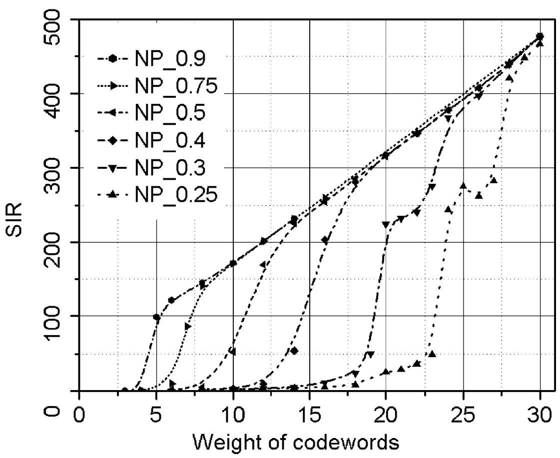

Fig. 12. SIR versus weight of the codewords for various value of NP.

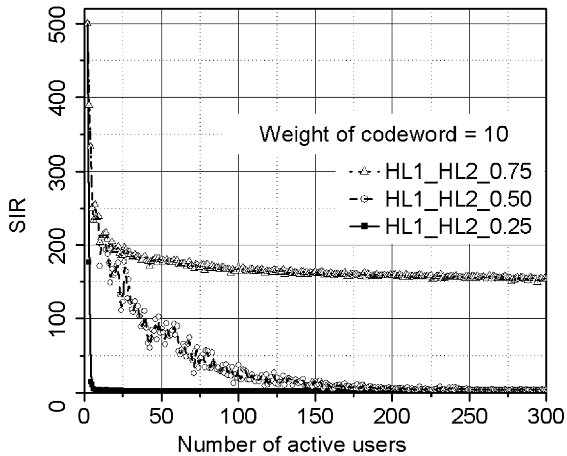

Fig. 13. SIR versus number of the active users for $w = 10$.

Figs. 14 and 15 show the bit error probability P_E of O-CDMA systems as a function of the mean signal photon count, $K_S = w\lambda_S T_C$, for various topology of the decoder, various value of *NP* and different value of *w*. From these Figs. it can be seen that the bit error probability becomes better as K_S increases because the difference between the received photon counts per chip time for “One” and “Zero“ data bit transmission is increasing. The effect of the weight of the codeword on this dependence can be seen by comparing Fig. 14 ($w = 10$) and Fig. 15 ($w = 15$). It can be seen that when all users of the O-CDMA system access the network simultaneously, the system with both optical HLs has much better performance than the systems without and with only the first optical HL.

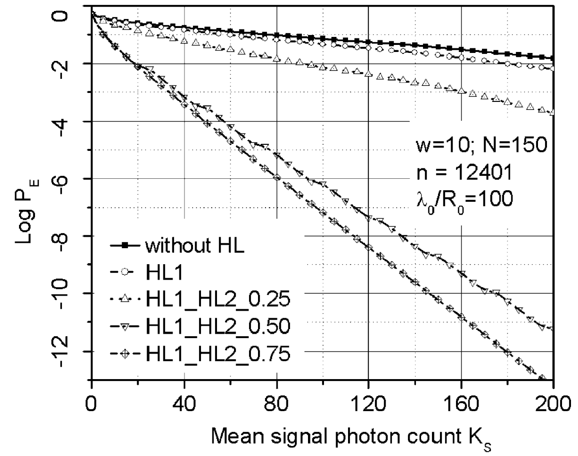

Fig. 14. Bit error probability of O-CDMA systems versus K_S for the following cases. The decoder without, with the first and with the both optical HLs for various value of *NP*. The system parameters are: $N = 150$, $n = 12{,}401$, $\lambda_0/R_0 = 100$ and $w = 10$.

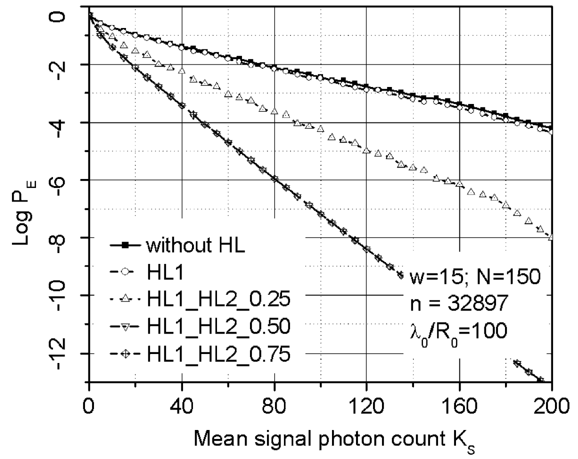

Fig. 15. Bit error probability of O-CDMA systems versus K_S for following cases. Decoder without, with first and with both optical HLs for various value of *NP*. The system parameters are: $N = 150$, $n = 32{,}897$, $\lambda_0/R_0 = 100$ and $w = 15$.

Fig. 16 shows the bit error probability of the O-CDMA systems with both optical HL P_E as a function of the number of active users for various value of *NP*. This figure depicts the effect of *NP* on this dependence. The P_E strongly depends on the number of active users in such a case when the decoder contains only the first optical HL.

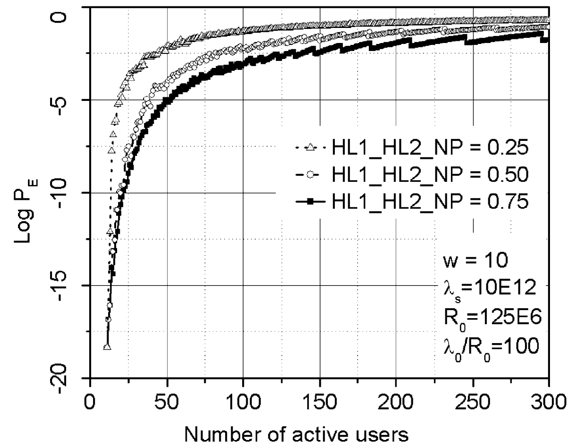

Fig. 16. Bit error probability versus number of the active users for the decoder with the both optical HLs and for various value of *NP*. The system parameters are: $w = 10$, $\lambda_S = 10E12, R_0 = 125E6$ and $\lambda_0/R_0 = 100$.

Fig. 17 shows the variation of P_E as a function of the weight of the codeword for different values of *NP*. We assume 150 active users of the system and a decoder with both optical HLs. From the dependence, for the case $NP = 0.75$, we can see that the dominant effect to P_E belongs to the MAI for the weight of the codeword approximately up to 8. For the weight of codeword greater than 8, the following effect has the dominant influence on

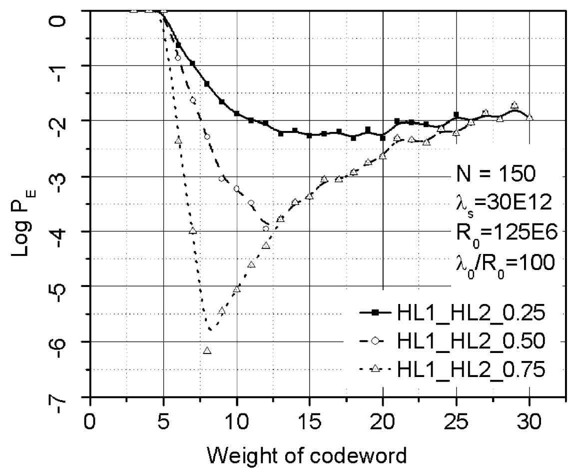

Fig. 17. Bit error probability versus the weight of the codewords for the decoder with the both optical HLs and for various value of *NP*. The system parameters are: $N = 150$, $\lambda_S = 30E12, R_0 = 125E6$ and $\lambda_0/R_0 = 100$.

P_E. With an increasing weight of the codeword also SIR increases but the mean signal photon count K_S is decreasing because the length of the codeword is increasing and T_C is decreasing. From this dependence it can be seen that an optimum weight of the codewords exits for achieving the minimum value of the P_E for a specified parameter of the CDMA system.

5. Conclusion

For the first time, the performance of the time spread on–off keying O-CDMA system with non-ideal optical hard-limiters has been analyzed in this paper. Shortened optical orthogonal codes have been employed as the signature codewords. As the performance merits were used the signal-to-interference ratio and the bit error probability. The dependencies of the signal-to-interference ratio and the bit error probability versus the weight of codeword and the number of active users in the system have been studied. The analysis shows that the second hard-limiter of the O-CDMA decoder has a dominant effect upon the signal-to-interference ratio. The dependence of bit error probability versus the weight of codewords has a local minimum; this allows to choose an optimum weight of the codewords for achieving the minimum bit error probability of O-CDMA.

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