

Code Cross-Correlation Effects on the Performance of Optical CDMA Systems in the Presence of Receiver Noises

S. M. Zabihi-Maddah

Faculty of Engineering, Ferdowsi University of Mashhad,
Mashhad, Iran
Email: zabihimaddah@stu-mail.um.ac.ir

M. Molavi Kakhki

Faculty of Engineering, Ferdowsi University of Mashhad,
Mashhad, Iran

Abstract — Increasing the number of simultaneous users is one of the challenging issues in incoherent and asynchronous optical CDMA systems. One solution is to increase the value of cross-correlation, λ_c . In [3] neglecting the effect of noise, optimum value of λ_c was obtained. In this work, with considering noise, the simultaneous effect of λ_c and transmitted power on the probability of bit error (pbe) is investigated. Our investigation is performed by employing OOC ($\lambda_c = 1$) and prime code ($\lambda_c = 2$) and active correlator is chosen for its robustness against the noise. The performance is analyzed for three common receiver structures, namely soft receiver (without optical hard limiter), single optical hard limiter (SHL) and double optical hard limiters (DHL). Our results show that under the same bandwidth efficiency, increasing λ_c in high power regimes decreases the pbe but increasing λ_c in low power regimes will increase pbe.

Keywords: Optical Code division multiple access (OCDMA), Hard limiter, Prime Code, Cross-Correlation.

I. INTRODUCTION

Optical CDMA (OCDMA) schemes have recently received substantial attention in local area networks. OCDMA offers several advantages in local area networks. OCDMA allows simultaneous users to send their data asynchronously through the assignment of unique signature sequence. This sequence is used to transmit bit "1" while nothing is sent for bit "0" (On-Off Keying). In the literature some kind of codes has been proposed for using as code sequence, i.e. optical orthogonal codes (OOCs) and prime codes.

In this paper, we study incoherent and asynchronous OCDMA systems. Multiple access interference (MAI) is always a serious problem in the performance of such systems. In order to reduce the MAI, the signature code must have small cross-correlation. An $(L, w, \lambda_a, \lambda_c)$ OOC is a collection of binary L-tuples with Hamming weight w such that the maximum out of phase autocorrelation is bounded by λ_a and the maximum cross-correlation is bounded by λ_c [1]. The signature codes with lower correlation will usually outperform the signature codes with higher correlation for the same number of the simultaneous users, (N). One of the problems associated with systems using OOCs is the small number of users. It has been shown that more users can be provided with

even better performance for an $(L, w+m, \lambda+m, \lambda)$ OOC compared with an (L, w, λ, λ) OOC [2]. As shown in [3] for the same number of users and the same length (L), the performance of $\lambda_c = 2$ OOC may surpass the performance of $\lambda_c = 1$ OOC. This is because $\lambda_c = 2$ OOC may have a much larger value of w , hence compensating the performance degradation. Using soft receiver (without HL) in [4] the pbe for $\lambda_c = 1$ and $\lambda_c = 2$ OOCs was computed. It has been shown in [5] that using optical hard limiter (HL) could enhance the bit error rate (BER) of OCDMA systems by excluding some MAI patterns. For $\lambda_c = c$ OOCs, where c is any arbitrary positive integer, the exact expression for the pbe using hard limited receiver has been given in [6]. Later, employing a different approach and using generalized OOCs with $\lambda_c = \lambda$, Mashhadi and Salehi found another expression [3].

There are two criteria for performing a comparison between two code sets of optical CDMA systems, namely bit error probability and bandwidth efficiency (BE). Performing a fair comparison, one can examine the system performance by one criteria while the other one is remained fixed. In other words, we are interested in choosing the code set which gives lower value of bit error probability, P_e , for a given pair of (L, N) or choosing the code set which gives higher BE, which is defined as $BE = \frac{N}{L}$ [7], for a minimum error probability $(P_{e \min})$.

Since OCDMA systems using OOC with $\lambda_c = 1$ suffer from low number of simultaneous users, an increasing interest has been focused on codes with higher cross-correlation values. For this reason, a performance of OCDMA system was analyzed employing AND logic gate receiver structure and generalized optical orthogonal code [3]. In the mentioned paper, the minimum bit error probability was obtained by firstly finding optimum value of λ_c (λ_{opt}), regardless of code weight and then using this value to determine the optimum value of code weight w_{opt} .

In all mentioned works the effect of receiver noises was not included. An analysis was performed by Kwon [8] to evaluate the pbe of OCDMA systems in presence of receiver noises employing OOC with $\lambda_c = 1$, electrical encoding and two receiver structures, namely soft receiver and using single hard limiter (SHL). It was shown that when the number of simultaneous users is much less than the pulsed laser's modulation extinction ratio and for both of mentioned receiver structure, OCDMA systems utilizing optical encoding perform in a similar way as their electrical encoding counterparts [9]. It should be noted that, OCDMA systems using double hard limiters (DHL) receivers and active correlator outperform their counterparts which are using logic gate receivers or chip level detection [10].

In this paper, in order to choose the optimum code, we study the effect of varying λ_c on code weight and we calculate bit error probability in the presence of receiver noises as well as interference. Our analysis are performed using active correlator and employing three common receiver structures, namely soft receiver, SHL and DHL for incoherent and asynchronous OCDMA systems using prime code ($\lambda_c = 2$). Furthermore, in all of the receivers APD is chosen as photo detector and its output is modeled by a Gaussian function and optical decoder is employed. Our results show that for a given (L, N), codes with lower values of λ_c could perform better than ones with greater values. It should also be noted that this better value of pbe, for low cross-correlation codes, is achieved in lower code weights in comparison with their high cross-correlation counterparts.

II. SYSTEM MODEL

In our system model, data bits drive a pulsed laser with a rate of $1/T_b$. Then, the output of the pulsed laser is conveyed to an array of tapped delay lines (optical encoder). After that, the encoded users data pass through a passive star coupler (PSC) and finally reach the output ports of PSC which the receivers are placed. In this work, we neglect the power loss in the output ports of PSC.

Figure 1 shows the model of soft receiver. The received signal is multiplied by a stored replica of desired code. The decoded signal is fed into an APD. The receiver integrates the APD output over a bit time $T_b = FT_c$. Then, by passing the signal through a sampler with frequency $1/T_b$, the decision variable Z is achieved. Lastly, by comparing Z with a threshold level Th , the final decision on the sent bit is made. If an optical HL is placed in front of the optical correlator, the receiver with SHL is obtained. Furthermore, by placing an optical HL before and one after the optical correlator, the receiver with DHL is obtained. It was shown that OCDMA systems using DHL outperform the systems using SHL and the later outperform OCDMA systems using soft receiver considering the effect of noise in high power regimes [11, 9].

The probability that a specified number of photons are absorbed from an incident optical field by an APD detector

over a chip time with duration T_c is given by Poisson distribution with rate λ_s , which is [8]:

$$\lambda_s = \frac{\eta P}{h\nu} \quad (1)$$

where P the received power in front of power splitter during a mark chip time when the desired user is transmits bit "1", η is the APD quantum efficiency with which the APD converts incident photons to photoelectrons, h is Plank's constant and ν is the optical frequency. Primary photoelectron-hole pairs in the APD detector undergo an avalanche multiplication process that results in the output of n electrons from the APD in the response to the absorption of $\lambda_s T_c$ primary photons on the average. By Representing λ as the total photon absorption rate due to signal and APD bulk leakage current, we have:

$$\lambda = \begin{cases} \lambda_s + I_b/e & \text{for bit "1"} \\ \lambda_s/M_e + I_b/e & \text{for bit "0"} \end{cases} \quad (2)$$

where e is an electron charge, I_b/e represents the contribution of the APD bulk leakage current to the APD output, and M_e is the modulation extinction ratio of the laser. It is shown that random variable (r.v.) Z could be approximated with a Gaussian r.v. with mean and variance of [8]:

$$\mu = \langle Z \rangle = G \left[c_s + \frac{I_b T_b}{e} \right] + \frac{I_s T_b}{e} \quad (3)$$

$$\sigma^2 = \text{var}(Z) = G^2 F_e \left[c_s + \frac{I_b T_b}{e} \right] + \frac{I_s T_b}{e} + \sigma_{th}^2 \quad (4)$$

where c_s the mean value of absorbed photon in T_b , G is the mean value of APD random gain and I_s is the surface leakage current which is inherently modeled in APD. F_e is the excess noise factor defined as $F_e = k_{eff} G + \left(2 - \frac{1}{G} \right) (1 - k_{eff})$ where k_{eff} is the effective ionization ratio and its value depends on the wavelength and material used in fabrication of photo detector. Also, σ_{th}^2 is thermal noise variance of APD and its value is related to system parameters as $\sigma_{th}^2 = \frac{2k_B T_r T_c}{e^2 R_L}$ where k_B is the Boltzmann constant, T_r is the receiver noise temperature and R_L is the receiver load resistor (see Table I) [8].

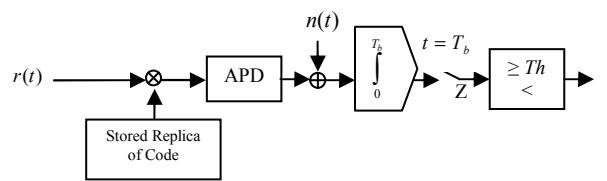


Figure 1-Model of soft receiver.

TABLE I. TYPICAL PARAMETER VALUES OF OCDMA SYSTEMS USING APD

Name	Symbol	Value
Laser frequency	ν	2.424×10^{14} Hz
APD quantum efficiency	η	0.6
APD average gain	G	100
Effective ionization ratio of APD	K_{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	100°K
Receiver load resistance	R_L	1030 Ω

III. EFFECT OF VARRYING λ_c ON CODE WEIGHT AND BIT ERROR PROBABILITY

An upper bound on pbe for OCDMA systems employing SHL and neglecting the effect of receiver noises using generalized OOC is given in [3]:

$$P_E = \frac{1}{2} + \frac{1}{2} \sum_{k=1}^w (-1)^k \binom{w}{k} \left[1 - \frac{w^2}{2\lambda L} \times \left(1 - \frac{(w-\lambda)(w-\lambda-1) \dots (w-\lambda-k+1)}{w(w-1) \dots (w-k+1)} \right)^{N-1} \right] \quad (5)$$

Consider two code set of OOC $\lambda_c=2$, $\lambda_c=3$ in a fixed BE. We are going to make a fair comparison between them. Set values of code length and the number of simultaneous users respectively as $L=289$ and $N=17$. Based on [3], (45)], one can get $\lambda_{opt}=3$ and then $w_{opt}=35$. Decreasing λ_c as $\lambda_c=2$ will result in $w_{opt}=17$. The given upper bound of two above code sets using (5) has been plotted in Figure 2. As can be seen from this figure, comparison of above two cases reveals that lower cross-correlation code set, i.e. $\lambda_c=2$, result in better performance in the lower value of code weights. The above result will be more interesting when we are taking transmitted power into account. This power is used for desired user when bit "1" has transmitted. This is due to the fact that for a fixed transmitted power - decreasing w - increases the signal to noise ratio during the desired (mark) chip times which directly leads to lower bit error probabilities. Furthermore, according to this figure, increasing code weight in low transmitted powers increases bit error probability when the effects of receiver noises are included. Among all code sets which their cardinality are greater than or equal to N , the code set with lower λ_c is preferable. Thus, λ_{opt} in the above example is $\lambda_{opt}=2$ and using Johnson bound the corresponding code weight is $w_{opt}=w_{max}=17$.

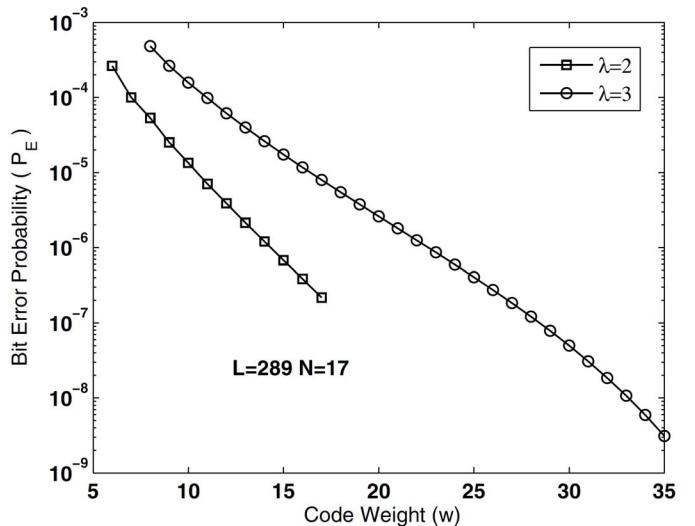


Figure 2- Bit error probability versus code weight for two coss-correlation for $L=289$, $N=17$.

A prime code can be shown $(p^2, p, p, 2)$. In the above example let $p=17$ and then constructs a prime code set. It is apparent that the parameters of this prime code set are close to an OOC with $\lambda_c=2$. In other words, considering the constraint on code weight causes prime code $(289, 17, 17, 2)$ with lower cross-correlation to be better than OOC with $\lambda_c=3$. It also worth noting that, considering $\lambda_a=p$, it's possible to choose values of code weight above p , but prime code is limited to have $w=p$. The performance of OCDMA systems using prime code is better than their counterparts using optimum OOC with $\lambda_{opt}=3$. Secondly, for low transmitted powers, less code weights results in better performance. Since there is not a closed form formula for the pbe of OOC with $\lambda_c=3$, a comparison is made between OCDMA systems employing OOC with $\lambda_c=2$, as a code with higher cross-correlation, and OCDMA systems employing OOC with $\lambda_c=1$, as a code with lower cross-correlation. Since we are also interested in making this comparison under fixed BE, prime code is chosen as an acceptable OOC with $\lambda_c=2$. To make the above comparison we have used the derived bit error probabilities of OCDMA system using OOC with $\lambda_c=1$ which are given in [8] and [9].

IV. PERFORMANCE ANALYSIS OF OCDMA SYSTEMS USING PRIME CODE

Let I_1 and I_2 be respectively the number of interfering users which hit exactly one and two marks of desired code in OCDMA systems using prime codes. Probability distribution function (pdf) of interference pattern has multinomial distribution with parameters $N-1$, q_1 and q_2 :

$$\Pr(l_1, l_2) = \frac{(N-1)!}{l_1! l_2! (N-1-l_1-l_2)!} \times q_1^{l_1} q_2^{l_2} (1-q_1-q_2)^{N-1-l_1-l_2} \quad (6)$$

where $q_2 = \frac{(p+1)(p-2)}{12p^2}$, $q_1 = \frac{2p^2+p+2}{6p^2}$ and $q_0 = \frac{7p^2-p-2}{12p^2}$ [12]. Moreover, it should be noted that the total number of interfering users is $l = l_1 + l_2$ and the total number of interfering pulses (marks) is $l_1 + 2l_2$.

A. Performance Analysis for OCDMA System with Soft Receiver

In this part we study the pbe of OCDMA systems using prime codes with soft receiver. We define the set A as:

$$A = \{l_1, l_2 \in \{0, 1, 2, \dots, N-1\} \mid l_1 + l_2 \leq N-1\} \quad (7)$$

As mentioned earlier, r.v. Z is Gaussian and has the conditional pdf as:

$$\begin{aligned} P_Z(z|I=i, \text{sent bit } b=j) &= \frac{1}{\sqrt{2\pi\sigma_j^2(i)}} \\ &\times \exp\left(\frac{-(z-\mu_j(i))^2}{2\sigma_j^2(i)}\right) \end{aligned} \quad (8)$$

where $j \in \{0, 1\}$, furthermore we have:

$$\begin{aligned} \Pr(\text{error}|\text{sent bit } b=0, Th) &= \sum_{l_1, l_2 \in A} Q\left(\frac{Th - \mu_0(l_1 + 2l_2)}{\sigma_0(l_1 + 2l_2)}\right) \times \Pr(l_1, l_2) \end{aligned} \quad (9)$$

$$\begin{aligned} \Pr(\text{error}|\text{sent bit } b=1, Th) &= 1 - \sum_{l_1, l_2 \in A} Q\left(\frac{Th - \mu_1(l_1 + 2l_2)}{\sigma_1(l_1 + 2l_2)}\right) \times \Pr(l_1, l_2) \end{aligned} \quad (10)$$

where $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-y^2/2} dy$ and we have:

$$\begin{aligned} \mu_j(i) &= GT_c \left[(wj+i)\lambda_s + \left(wN - (wj+i) \frac{\lambda_s}{M_e} + L \frac{I_b}{e} \right) \right] \\ &+ LT_c \frac{I_s}{e} \end{aligned} \quad (11)$$

$$\begin{aligned} \sigma_j^2(i) &= G^2 F_e T_c \left[(wj+i)\lambda_s + \left(wN - (wj+i) \frac{\lambda_s}{M_e} + L \frac{I_b}{e} \right) \right] \\ &+ L \left(T_c \frac{I_s}{e} + \sigma_{th}^2 \right) \end{aligned} \quad (12)$$

Finally, the bit error probability is obtained as:

$$\Pr(\text{error}) = \frac{1}{2} \times \min_{Th} \left\{ \Pr(\text{error}|\text{sent bit } b=0, Th) + \Pr(\text{error}|\text{sent bit } b=1, Th) \right\} \quad (13)$$

B. Performance Analysis for OCDMA System with SHL

In this part we study the pbe of OCDMA systems using prime codes with SHL receiver in presence of receiver noises. Achieving this goal, it is essential to have $\Pr(|\mathbf{i}|=m \mid \mathbf{i})$ where, \mathbf{i} is the interference pattern vector and $|\mathbf{i}|$ is its weight or number of nonzero elements of \mathbf{i} [6]. We obtain:

$$\begin{aligned} &\Pr(\text{error}|\text{sent bit } b=0, Th) \\ &= \sum_{l_1, l_2 \in A} \sum_{j=0}^{\min(w, l_1+2l_2)} \sum_{m=0}^j Q\left(\frac{Th - \mu_0(j)}{\sigma_0(j)}\right) \binom{w}{j} \times \\ &(-1)^{j-m} \binom{j}{m} \left(q_0 + q_1 \frac{m}{w} + q_2 \frac{\binom{m}{2}}{\binom{w}{2}} \right)^{N-1} \times \Pr(l_1, l_2) \end{aligned} \quad (14)$$

$$\Pr(\text{error}|\text{sent bit } b=1, Th) = 1 - Q\left(\frac{Th - \mu_1}{\sigma_1}\right) \quad (15)$$

where in these two equations we have:

$$\mu_0(j) = GT_c \left[j\lambda_s + L \frac{I_b}{e} \right] + LT_c \frac{I_s}{e} \quad (16)$$

$$\sigma_0^2(j) = G^2 F_e T_c \left[j\lambda_s + L \frac{I_b}{e} \right] + L \left(T_c \frac{I_s}{e} + \sigma_{th}^2 \right) \quad (17)$$

$$\mu_1 = GT_c \left[w\lambda_s + L \frac{I_b}{e} \right] + LT_c \frac{I_s}{e} \quad (18)$$

$$\sigma_1^2 = G^2 F_e T_c \left[w\lambda_s + L \frac{I_b}{e} \right] + L \left(T_c \frac{I_s}{e} + \sigma_{th}^2 \right) \quad (19)$$

C. Performance Analysis for OCDMA System with DHL

In this part we study the pbe of OCDMA system using prime code with DHL receiver. In this case, the bit error is occurred if interfering users hit all the mark positions of desired users' code, i.e. $|\mathbf{i}| = w$.

$$\begin{aligned} &\Pr(\text{error}|\text{sent bit } b=0, Th) \\ &= \sum_{l_1, l_2 \in A} \sum_{m=0}^w Q\left(\frac{Th - \mu_{(pass)}}{\sigma_{(pass)}}\right) (-1)^{w-m} \end{aligned} \quad (20)$$

$$\begin{aligned}
& \times \binom{w}{m} \left(q_0 + q_1 \frac{m}{w} + q_2 \frac{\binom{m}{2}}{\binom{w}{2}} \right)^{N-1} \Pr(l_1, l_2) \\
& + \sum_{l_1, l_2 \in A} \sum_{j=0}^{\min(w-1, l_1+2l_2)} \sum_{m=0}^j Q\left(\frac{Th - \mu_{(block)}}{\sigma_{(block)}}\right) \\
& \times (-1)^{j-m} \binom{w}{j} \binom{j}{m} \\
& \times \left(q_0 + q_1 \frac{m}{w} + q_2 \frac{\binom{m}{2}}{\binom{w}{2}} \right)^{N-1} \Pr(l_1, l_2) \\
\Pr(\text{error} | \text{sent bit } b = 1, Th) &= 1 - Q\left(\frac{Th - \mu_{(pass)}}{\sigma_{(pass)}}\right) \quad (21)
\end{aligned}$$

where in these two equations we have [9]:

$$\mu_{(block)} = GLT_c \frac{I_b}{e} + LT_c \frac{I_s}{e} \quad (22)$$

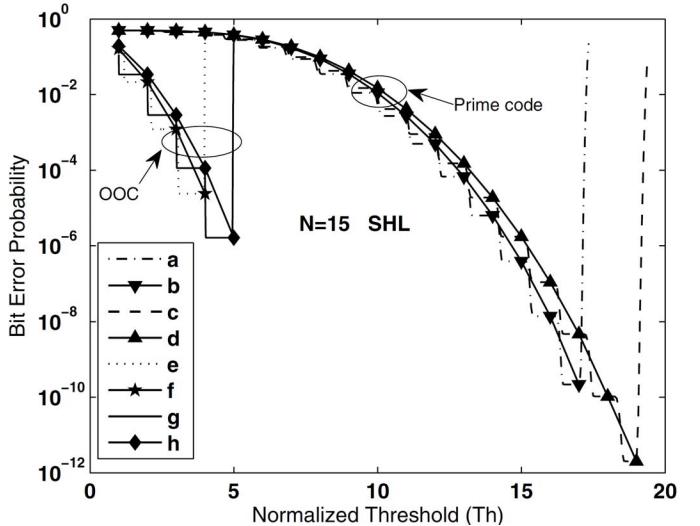
$$\sigma_{(block)}^2 = G^2 FL_e T_c \frac{I_b}{e} + L \left(T_c \frac{I_s}{e} + \sigma_{th}^2 \right) \quad (23)$$

$$\mu_{(pass)} = GT_c \left[w \lambda_s + L \frac{I_b}{e} \right] + LT_c \frac{I_s}{e} \quad (24)$$

$$\sigma_{(pass)}^2 = G^2 F_e T_c \left[w \lambda_s + L \frac{I_b}{e} \right] + L \left(T_c \frac{I_s}{e} + \sigma_{th}^2 \right) \quad (25)$$

V. NUMERICAL RESULTS

In this section, our numerical results for OCDMA systems employing prime code and OOC for three different receiver structures, namely soft receiver, SHL and DHL are presented. In these calculations parameter values given in Table I are used. Throughout this section, by "Normalized Threshold" we mean the threshold level which is fitted appropriately to cover all variations of our plots. It is noted that by $-P_{tr}$ we mean that the transmitted laser power of desired user during T_b when the transmitted bit is "1". The bit error probability for OCDMA systems utilizing SHL receiver and using prime codes and OOCs versus normalized threshold are plotted in Figure 3. Equations (14), (15), (13) with parameter set of $(N = 15, p = 17)$ and $(N = 15, p = 19)$ have been used to plot this figure. All of curves in this figure have been plotted for $P_{tr} = -20\text{dBW}$. Our numerical results are also compared with the ideal link [6, (16)]. Two optical orthogonal code sets of



a: $(N=15, p=17)$ and c: $(N=15, p=19)$ Prime code with noise $P_{tr} = -20\text{dBW}$ using (13-19); b: $(N=15, p=17)$ and d: $(N=15, p=19)$ Prime code ideal link [6, (16)]; e: $(N=15, L=289, w=4)$ and g: $(N=15, L=361, w=5)$ OOC with noise $P_{tr} = -20\text{dBW}$ [9, (26), (35), (40)]; f: $(N=15, L=289, w=4)$ and h: $(N=15, L=289, w=5)$ OOC ideal link [5, (34)].

Figure 3- Bit error probability versus normalized threshold using prime code and OOC employing SHL receiver.

$(L = 289, w = 4, N = 15)$, $(L = 361, w = 5, N = 15)$ which are equivalent to the previous code sets from the BE point of view have also been presented in Figure 4. Bit error probability of OCDMA systems using SHL in their receiver structure is calculated using [9, (26), (35), (40)]. For plotting the ideal link we have also used [5, (34)].

A comparison of OCDMA systems utilizing DHL receiver using prime code and OOC versus transmitted power is made in figure 4. Two fair comparisons are made between prime code and OOC in a fixed bandwidth efficiency. Choosing $N=19$ and setting $p=19$, we have the prime code family of $(361, 19, 19, 2)$ and its OOC counterpart is the family of $(361, 4, 1, 1)$. As can be seen from this figure, the performance of systems using prime code is better than ones using OOC when the transmitted laser power is greater than -52.5dBW . The performance superiority of systems using OOC regards to systems using prime code is because of having less code weight and therefore receiving less noise power.

Figures 5 and 6 show bit error probability versus number of simultaneous users for both OOCs and prime codes and employing DHL receiver when the received laser power is equal to -50dBW and -55dBW , respectively. For example, for making a comparison between prime code and OOC in a fixed BE in figure 5, let $p=17$, hence, the maximum number of simultaneous users $N_{max}=17$. OOC with the parameter set of $(L = 289, w = 4, \lambda_a = 1, \lambda_c = 1)$ is assumed. As can be seen from this figure, OCDMA systems using prime code outperform ones using OOC considerably. But for lower transmitted power (e.g. -55dBW) OCDMA systems using OOC with $\lambda_c = 1$ perform better than ones using prime code (see figure 6).

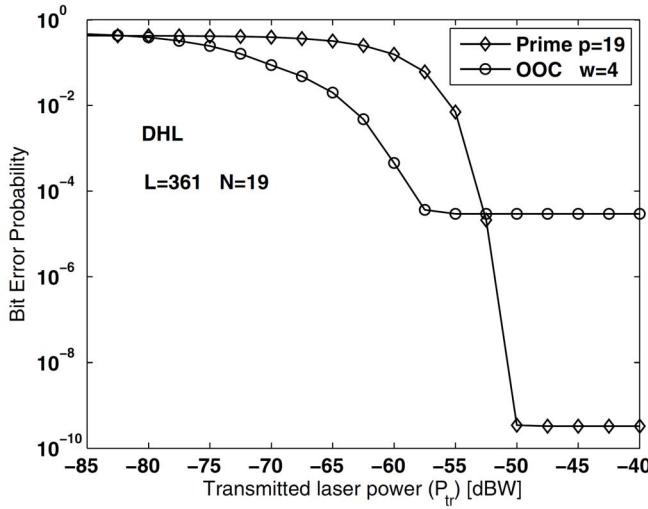


Figure 4-Bit error probability versus transmitted laser power using DHL receiver for prime code and OOC.

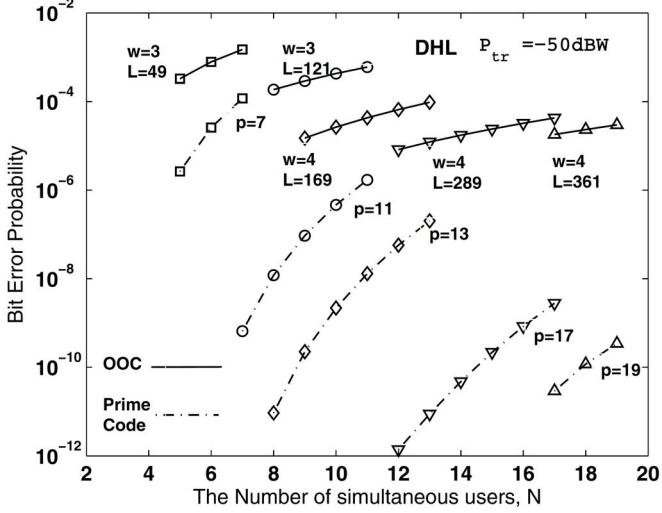


Figure 5- Bit error probability versus number of simultaneous users at fixed bandwidth efficiency.

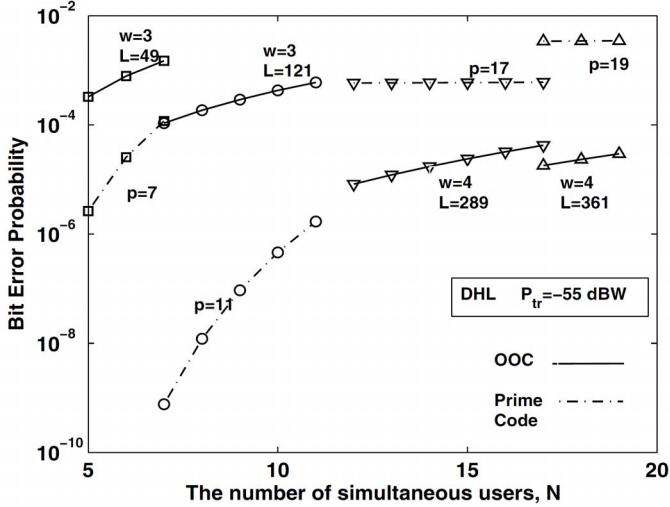


Figure 6- Bit error probability versus number of simultaneous users at fixed bandwidth efficiency.

VI. CONCLUSION

In this paper, we studied asynchronous fiber optic CDMA systems employing codes with $\lambda_c = 2$ in the presence of receiver noises. We derived a closed form formula for each receiver structure, namely soft receiver, SHL and DHL. The bit error probability of systems using prime code was compared with their counterparts using OOC. We concluded that increase the value of λ_c from $\lambda_c = 1$ to $\lambda_c = 2$ by itself could not make the performance better or worse but it depends on transmitted laser power. In other words, for high transmitted laser powers, increasing the value of λ_c which is led to increasing code weight (for achieving minimum bit error probability) will enhance the performance. But, for low transmitted powers, decreasing the value of λ_c which is led to decreasing code weight will enhance the performance.

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