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Impact and Mitigation of Noise in Optical 2D Techniques Using ($n, w, \lambda_a, \lambda_c$) Optical Orthogonal Codes for Optical CDMA

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The performance of two dimensional (2D) hybrid wavelength/time optical code division multiple access (OCDMA) system is affected severely by the presence of noise at its physical layer. This noise is present in the guise of multiple access interference (MAI) and beat noise in OCDMA systems and degrades its performance. In this paper an attempt has been made to analyze the impact of noise in OCDMA system using four different coding schemes. The mitigation of noise is then done by using either optical hard limiter (OHL) or by utilizing coherent detection for all these schemes. These codes use synchronized quadratic congruence sequences (SQC), synchronized prime procession (SPP), prime code sequences (PC) and synchronized prime sequences (SPS) for wavelength hopping and ($n, w, \lambda_a, \lambda_c$) one dimensional optical orthogonal codes for time spreading respectively. The code with heavier code weight or lower values of auto- and cross- correlation function performs the best with noise mitigation techniques. Investigations reveal that SQC/OOC coding scheme in combination with OHL and PC/OOC scheme in combination with coherent detection outperforms in comparison to other techniques.

Keywords: Optical orthogonal codes, Multiple access interference, SQC/OCC, PC, SPS, Optical hard limiter (OHL), Coherent detection.

1 Introduction

OCDMA technique has been accepted as one of the competitive candidate for next generation high speed future optical networks due to its ability for simplified and decentralized network control, all optical processing, improved spectral efficiency, support for bursty traffic, fully asynchronous transmission and above all enhanced security of information[1]. Though OCDMA system has considerable features on the networking level yet its success lies primarily in the properties of the unique optical codes used for spreading the data. The design of optimum codes with ideal auto- and cross- correlation properties is a challenging field in OCDMA[2]. The quest to come up with "perfect" code that is robust to multiple access interference, possess a large cardinality, support heavier code weight without increasing the number of available wavelengths is never ending. However, noise, on the other hand is the ever present disturbance in any practical CDMA system. It affects the performance of system at its physical layer and decreases the maximum number of users in the system due to the presence of multiple access interference (MAI) and beat noise. MAI results when many users simultaneously share the same frequency allocation and interfere with each other. This is also caused due to non-ideal orthogonal property of the optical codes. Due to random time offsets between the signals, the interference comes into existence that makes it impossible to design the code to be completely orthogonal[3]. With increase in number of active users, MAI increases that result in degradation of system performance. Secondly, beat noise is produced by the collision of electrical fields generated by signal, spontaneous emission and local oscillator. At the receiver side, photo detector generates a photocurrent along with several side components. These components come into existence when the noise electric field beats against the signal field and the fields of other optical noise components due to square law detection[4]. As noise can severely degrade the performance of any OCDMA system, so one of the important criteria for the choice of code in practical OCDMA system is their tolerance towards noise.

Several different methods have been proposed by various researchers to improve the system performance in the presence of noise. MAI and beat noise both can be reduced to a great extent by using

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optical hard limiter (OHL) and coherent (heterodyne) detection receiver. OHL is a non linear device that is capable of limiting the received optical power to a threshold level. The properties of material used for the fabrication of limiters are responsible for controlling the intensity of high optical pulses[5]. According to Dang *et al.*[6], at a particular wavelength, only those signals that possess peak power larger than or equal to the threshold can pass through the OHL. Another method to combat with beat noise and MAI is coherent or heterodyne detection. Pham *et al.*[7], have proposed the use of heterodyne detection for optical systems to improve their performance. Heterodyne detection is a type of coherent detection techniques that consists of a local oscillator (LO), with different frequency in comparison to the carrier frequency at receiver. The local oscillator frequency is coherently mixed with the received signal. This method of detection provided with lesser error probability and with high signal to beat-noise ratio along with uniform phase difference between two orthogonal signals[8].

The contribution of this manuscript is to analyze and compare the impact of MAI and beat noise on four different coding schemes and to apply optical hard limiter (OHL) method as well as heterodyne detection to combat with these effects to improve the performance of system. These coding schemes are SQC/OOC, SPP/OOC, PC/OOC and SPS/OOC. The main purpose of the research is to find robust coding scheme that can withstand the effects of MAI and beat noise using either OHL or heterodyne detection technique. The difference in these codes is due to the value of maximum auto- and cross- correlation functions. The results are reported on the basis of error probability for different number of users simultaneously accessing the system at various parameters.

The paper is organized in the following manner. Section I introduces the basic concepts of OCDMA and type of noise that adversely affect the system performance along with the methods to combat with these effects. Section II describes the system model. Section III analyses the performance of these coding schemes with and without the presence of noise and it also includes the enhancement in performance using OHL and coherent detection at the receiver. Section IV confirms the results with the help of numerical examples. Section V presents the conclusion of paper.

System Description

A simple block diagram of the system including MAI and beat noise using a heterodyne (coherent) detection/optical hard limiter is shown in Fig. 1.

At the transmitter side, optical pulse generator is used to generate the carrier light pulses which are transferred to the optical modulator to modulate the user defined data. Logical data in form of 0s & 1s is first converted in to electrical form by using non return-to-zero (NRZ) format and then transferred to optical modulator. An optical modulator then modulates the data with the carrier signal. After modulation, the signal is transferred to encoder that encodes the binary data into chip pulses. Generally, an array of fiber bragg gratings (FBGs) is used as encoder and decoder in the system for a particular set of code. Two different kinds of noise are included in the system: one is MAI that occurs within the network itself due to multiple users at the same time and beat noise at the detector stage. The received signal at the receiver side is first mixed with the local oscillator signal coherently with the help of coupler and then passed to low pass filter for coherent detection process. In coherent detection, carrier signal same as that used at transmitter side is produced by the local oscillator and mixed with the received one to detect the target code from the transmitter by comparing the values of auto- and cross- correlation with the help of threshold detector. Coherent detection is implemented in the receiver side as the value of probability of error using this technique depend upon the average hit probability of the code and data & MAI currents that can be calculated easily by using the equations mentioned in the next section. Optical hard limiter is used prior to detector circuit to limit the amplitude of high optical pulses. The last stage is threshold

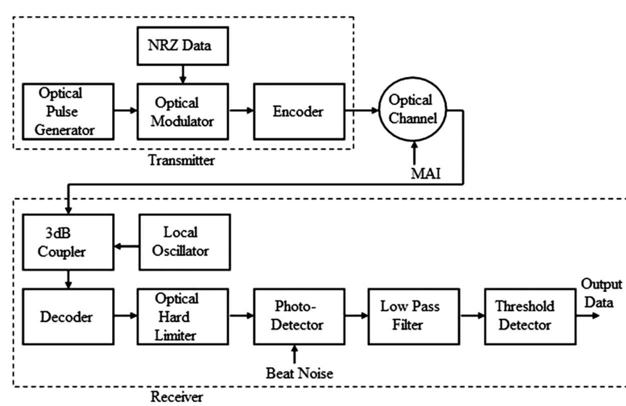

Fig. 1 — System Model

detector that provides the output in binary data format by using some hypothesis. Bit "1" is sent when the integrated current for a time period of one bit is higher than the threshold level and vice-versa.

Performance Analysis of Codes

This section deals with the analysis of each of the four coding schemes individually under the effect of MAI, beat noise and then the mitigation of these effects is also presented applying OHL and coherent detection.

Effect of MAI

Multiple access interference is caused when many users share the same transmission channel at the same time. W. C. Kwong *et al.*[9] proposed the following generic equation for MAI:

$$P_e = \frac{1}{2}\sum_{i=Th}^{K-1}\binom{K-1}{i} q^i (1-q)^{K-1-i} \quad \ldots (1)$$

Here, K stands for the number of simultaneous users; Th is pre-determined threshold of the receiver and is equal to the weight of code. The equation for q (average probability) is defined separately for each coding scheme.

1.1 PC/OOC

The average hit probability q_{PC} is calculated by using the equation as follows:

$$q_{PC} = \frac{1}{p} q^0 + \frac{p-1}{p} q^i \quad \ldots (1.1.1)$$

In the above equations q^0 and q^i are said to denote the probability of getting one hit between the desired and any interfering multi wavelength code in the code set. The equations for q^0 and q^i are obtained from[9]:

$$q^0 = \frac{w^2 (\Phi_{OOC}p-1)}{2N_{OOC}(\Phi_{OOC}p^2-1)} \quad \ldots (1.1.2)$$

$$q^i = \frac{w^2 (\Phi_{OOC}p-1)+(w-1)^2}{2N_{OOC}(\Phi_{OOC}p^2-1)} \quad \ldots (1.1.3)$$

By substituting the values of q in Eq. (1), the equation for error probability of PC/OOC codes under MAI is obtained. The resulting equation is:

$$P_e = \frac{1}{2}\sum_{i=Th}^{K-1}\binom{K-1}{i} {q_{PC}}^i (1-q_{PC})^{K-1-i} \quad \ldots (1.1.4)$$

1.2 SPS/OOC

The hard limiting error probability (HEP) for SPS/OOC as proposed by Jen-Hao Tien *et al.*[10] is as follows:

$$P_e \leq \frac{1}{2}\sum_{i=0}^{w}(-1)^i\binom{w}{i}\left[q_{2,0} + q_{2,1}\frac{(w-i)}{w} + q_{2,2}\frac{(w-i)(w-i-1)}{w(w-1)}\right]^{K-1} \quad \ldots (1.2.1)$$

Here, K is the number of simultaneous users and $q_{i,j}$ is the probability of getting j number of hits in a time slot for maximum cross-correlation value of i. The equations for $q_{2,0}$, $q_{2,1}$ and $q_{2,2}$ are given by:

$$q_{2,1} = \frac{1}{p} q_1^0 + \frac{p-1}{p} q_1^i \quad \ldots (1.2.2)$$

$$q_{2,2} = \frac{p-1}{p} q_2^i \quad \ldots (1.2.3)$$

$$q_{2,0} + q_{2,1} + q_{2,2} = 1 \quad \ldots (1.2.4)$$

Now $q_{2,0} = 1 - q_{2,1} - q_{2,2}$. Substituting this value in Eq. (1.2.1), we get

$$P_e \leq \frac{1}{2}\sum_{i=0}^{w}(-1)^i\binom{w}{i}\left[1 - q_{2,1} - q_{2,2} + q_{2,1}\frac{(w-i)}{w} + q_{2,2}\frac{(w-i)(w-i-1)}{w(w-1)}\right]^{K-1} \quad \ldots (1.2.5)$$

Comparing Eqs. (1) and (1.2.5), the equation for average hit probability *i.e.* q_{SPS} is found to be as:

$$q_{SPS} = q_{2,1} + q_{2,2} - q_{2,1}\frac{(w-i)}{w} - q_{2,2}\frac{(w-i)(w-i-1)}{w(w-1)} \quad \ldots (1.2.6)$$

The equation for error probability of SPS/OOC under MAI condition has been deduced by substituting the value of q_{SPS} as defined by Eq. (1.2.6) into Eq. (1). The resulting equation is as follows:

$$P_e = \frac{1}{2}\sum_{i=Th}^{K-1}\binom{K-1}{i} {q_{SPS}}^i (1-q_{SPS})^{K-1-i} \quad \ldots (1.2.7)$$

1.3 *SPP/OOC*

The hard limiting error probability (HEP) for SPP/OOC is given by[11]:

$$P_e \leq \frac{1}{2}\sum_{j=Th}^{w}\binom{w}{j}\sum_{i=0}^{j}(-1)^{j-i}\binom{j}{i}\left[q_0 + q_1\frac{(w-i)}{w} + q_2\frac{(w-i)(w-i-1)}{w(w-1)}\right]^{K-1} \quad \ldots (1.3.1)$$

Here, K denotes the number of simultaneous users and Th is the preset decision threshold. If q_i is the probability of number of hits in i time slot, then we have:

$$q_1 = \frac{1}{p}q_1^0 + \frac{p-1}{p}q_1^i \quad \ldots (1.3.2)$$

$$q_2 = \frac{1}{p}q_2^0 + \frac{p-1}{p}q_2^i \quad \ldots (1.3.3)$$

$$q_0 + q_1 + q_2 = 1 \quad \ldots (1.3.4)$$

Thus $q_0 = 1 - q_1 - q_2$ .Substituting this in Eq. (1.3.1), the equation for probability of error reduced to:

$$P_e \leq \frac{1}{2}\sum_{j=Th}^{w}\binom{w}{j}\sum_{i=0}^{j}(-1)^{j-i}\binom{j}{i}\left[1 - q_1 - q_2 + q_1\frac{(w-i)}{w} + q_2\frac{(w-i)(w-i-1)}{w(w-1)}\right]^{K-1} \quad \ldots (1.3.5)$$

Thus, by comparing Eq. (1.3.1) and (1.3.5), the equation for average hit probability *i.e.*q_{SPP} is found to be as:

$$q_{SPP} = q_1 + q_2 - q_1\frac{(w-i)}{w} - q_2\frac{(w-i)(w-i-1)}{w(w-1)} \quad \ldots (1.3.6)$$

Therefore, error probability in the presence of MAI for SPP/OOC has been deduced by substituting q_{SPP} into Eq. 1. The resulting equation is as follows:

$$P_e = \frac{1}{2}\sum_{i=Th}^{K-1}\binom{K-1}{i} q_{SPP}{}^{i}(1 - q_{SPP})^{K-1-i} \quad \ldots (1.3.7)$$

1.4 SQC/OOC

The hard limiting error probability (HEP) as given by G. C. Yang *et al* [12] is:

$$P_e \leq \frac{1}{2}\sum_{i=0}^{w}(-1)^{i}\binom{w}{i}\left[q_0 + q_1\frac{(w-i)}{w} + q_2\frac{(w-i)(w-i-1)}{w(w-1)}\right]^{K-1} \quad \ldots (1.4.1)$$

Here, K denotes the number of simultaneous users. q_i denotes the probability of cross-correlation function in i time slot:

$$q_2 = \frac{1}{p^2}q_2^0 + \frac{p^2-1}{p^2}q_2^1 \quad \ldots (1.4.2)$$

$$q_1 = \frac{w}{2pn} - 2q_2^1 \quad \ldots (1.4.3)$$

$$q_0 + q_1 + q_2 = 1 \quad \ldots (1.4.4)$$

Thus, $q_0 = 1 - q_1 - q_2$ .Substituting this in Eq. (1.4.1), the resulting equation becomes:

$$P_e \leq \frac{1}{2}\sum_{i=0}^{w}(-1)^{i}\binom{w}{i}\left[1 - q_1 - q_2 + q_1\frac{(w-i)}{w} + q_2\frac{(w-i)(w-i-1)}{w(w-1)}\right]^{K-1} \quad \ldots (1.4.5)$$

The Equation for average hit probability *i.e.* q_{SQC} can be found from Eq. (1.4.1) and (1.4.5) as:

$$q_{SQC} = q_1 + q_2 - q_1\frac{(w-i)}{w} - q_2\frac{(w-i)(w-i-1)}{w(w-1)} \quad \ldots (1.4.6)$$

The error probability in the presence of MAI for SQC/OOC has been deduced by substituting q_{SQC}into Eq.1. The resulting equation is as follows:

$$P_e = \frac{1}{2}\sum_{i=Th}^{K-1}\binom{K-1}{i} q_{SQC}{}^{i}(1 - q_{SQC})^{K-1-i} \quad \ldots (1.4.7)$$

2 Effect of Beat Noise

Noise is the prime reason behind the corruption of signal and its occurrence is very much random in the system. It can be internal or external to the system. Beat noise occurs due to beating between the pulses of electric and signal field against itself, and against the fields of other optical noise components. The generalized equation for error probability in the presence of beat noise is proposed by L. Tancevski[4] and is given as:

$$P_e = \sum_{i=1}^{K-1}\binom{K-1}{i}\frac{1}{2}\{Q(SNR_0) + Q(SNR_1)\}q^{i}(1-q)^{K-1-i} \quad \ldots (2)$$

$$SNR_0 = \frac{p_s P_d D - jP_c}{\sqrt{2P_c P_c \left(\frac{j}{2}\right)\frac{1}{p_s}}} \quad ; SNR_1 = \frac{p_s P_d + jP_c - p_s P_d D}{\sqrt{2jP_d P_c + 2P_c P_c \left(\frac{j}{2}\right)\frac{1}{p_s}}}$$ … (2(a) & (b))

Here, p_s is the available wavelengths (=*w*), P_d and P_c are optical powers of data and interferer pulses respectively, *D* is the threshold (=1/2). In equation (2) it is assumed that out of *K* simultaneous users, *I* users out of possible *K*-1 are transmitting "1" (with probability ½) and at the time of thresholding, *j* pulses among *I* are deposited to form the autocorrelation peak. For the purpose of analysis P_d and P_c are taken as one here. The values for SNR_0 and SNR_1 are calculated using equations (2(a) & (b)) for each code.

2.1 PC/OOC

The Equation for PC/OOC in the presence of beat noise has been deduced by substituting the value of q_{PC} from Eq. 1.1.1 in Eq. (2). The resulting equation is:

$$P_e = \sum_{i=1}^{K-1} \binom{K-1}{i} \frac{1}{2} \{Q(SNR_0) + Q(SNR_1)\} q_{PC}{}^{i} (1 - q_{PC})^{K-1-i}$$ … (2.1.1)

2.2 SPS/OOC

The error probability in the presence of beat noise for SPS/OOC has been deduced by substituting q_{SPS} from Eq. (1.2.6) into Eq. (2). The resulting equation is:

$$P_e = \sum_{i=1}^{K-1} \binom{K-1}{i} \frac{1}{2} \{Q(SNR_0) + Q(SNR_1)\} q_{SPS}{}^{i} (1 - q_{SPS})^{K-1-i}$$ … (2.2.1)

2.3 SPP/OOC

The error probability in the presence of beat noise for SPP/OOC has been deduced by substituting q_{SPP} from Eq. (1.3.6) into Eq. (2). The resulting equation is:

$$P_e = \sum_{i=1}^{K-1} \binom{K-1}{i} \frac{1}{2} \{Q(SNR_0) Q(SNR_1)\} q_{SPP}{}^{i} (1 - q_{SPP})^{K-1-i}$$ … (2.3.1)

2.4 SQC/OOC

The error probability in the presence of beat noise for SQC/OOC has been deduced by substituting q_{SQC} from Eq. (1.4.6) into Eq. (2). The resulting equation is:

$$P_e = \sum_{i=1}^{K-1} \binom{K-1}{i} \frac{1}{2} \{Q(SNR_0) + Q(SNR_1)\} q_{SQC}{}^{i} \left(1 - q_{SQC}\right)^{K-1-i}$$ … (2.4.1)

3 Effect of Optical Hard Limiter (OHL)

An optical hard limiter is a non linear device that is capable of limiting the optical power at a particular wavelength to a fixed threshold at the receiver. A receiver with hard limiter as component is known as hard-limiting receiver and the term hard limiting error probability is used instead of error probability. The hard limiting error probability (HEP) for PC/OOC as given by following equation[10]:

$$P_e \leq \frac{1}{2} \sum_{i=0}^{Th} (-1)^{i} \binom{w}{i} \left[1 - \frac{q_{PC} i}{w}\right]^{K-1}$$ … (3.1)

Here *K* denotes the number of simultaneous users and q_{PC} is obtained by Eq. (1.1.1). The error probability for SPS/OOC, SPP/OOC and SQC/OOC codes are given by Eq. (1.2.1), (1.2.7) and (1.4.1) respectively.

4 Effect of Coherent Detection

Coherent detection is one of the methods to combat with beat noise and to increase the number of users accessing the system. It is a type of detection technique that mixes the local oscillator frequency with the received signal coherently. The generic equation for error probability when coherent detection is employed in the receiver is obtained from[7,8] and is given as:

$$P_e = \sum_{i=1}^{K-1} \binom{K-1}{i} \frac{1}{2} \{Q(SNR_0) + Q(SNR_1)\} q^{i} (1 - q)^{K-1-i}$$ … (4)

Here *K* is the number of simultaneous users, q is the average hit probability defined separately for each code. SNR_0 and SNR_1 can be obtained as under:

$$SNR_b = \frac{(i_b - i_D)^2}{i_{nb}^2}$$ … (4.1)

i_b, where *b* may be bit "0" or bit "1" is the sum of data and MAI currents. The value of SNR_0 and SNR_1 will remain the same for all the techniques.

4.1 PC/OOC

The equation for PC/OOC for coherent detection has been deduced by substituting the value of q_{PC} (defined by Eq. (1.1.1)) in Eq. (4). The resulting equation is:

$$P_e = \sum_{i=1}^{K-1} \binom{K-1}{i} \frac{1}{2} \{Q(SNR_0) + Q(SNR_1)\} q_{PC}{}^{i} (1 - q_{PC})^{K-1-i} \quad \ldots (4.1.1)$$

4.2 SPS/OOC

The equation for SPS/OOC for coherent detection has been deduced by substituting the value of q_{SPS} (defined by Eq. (1.2.6)) in Eq. (4). The resulting equation is:

$$P_e = \sum_{i=1}^{K-1} \binom{K-1}{i} \frac{1}{2} \{Q(SNR_0) + Q(SNR_1)\} q_{SPS}{}^{i} (1 - q_{SPS})^{K-1-i} \quad \ldots (4.2.1)$$

4.3 SPP/OOC

The equation for SPP/OOC for coherent detection has been deduced by substituting the value of q_{SPP} (defined by Eq. (1.3.6)) in Eq. (4). The resulting equation is:

$$P_e = \sum_{i=1}^{K-1} \binom{K-1}{i} \frac{1}{2} \{Q(SNR_0) + Q(SNR_1)\} q_{SPP}{}^{i} (1 - q_{SPP})^{K-1-i} \quad \ldots (4.3.1)$$

4.4 SQC/OOC

The equation for SQC/OOC for coherent detection has been deduced by substituting the value of q_{SQC} (defined by Eq. (1.4.6)) in Eq. (4). The resulting equation is:

$$P_e = \sum_{i=1}^{K-1} \binom{K-1}{i} \frac{1}{2} \{Q(SNR_0) + Q(SNR_1)\} q_{SPP}{}^{i} (1 - q_{SPP})^{K-1-i} \quad \ldots (4.4.1)$$

Numerical Examples

After analyzing the effect of MAI, beat noise and methods to combat with this noise for each code individually, this section presents a comparative analysis of the error probability of the four codes described in section III. The comparison is made for number of wavelengths m = 7, 11 and 13 and code lengths of these codes is taken similar. Figure 2(a) compares the error probability, from (1.1.4,1.2.7, 1.3.7& 1.4.7) for the four codes with respect to number of users in the presence of MAI at m = 7. It is clear from

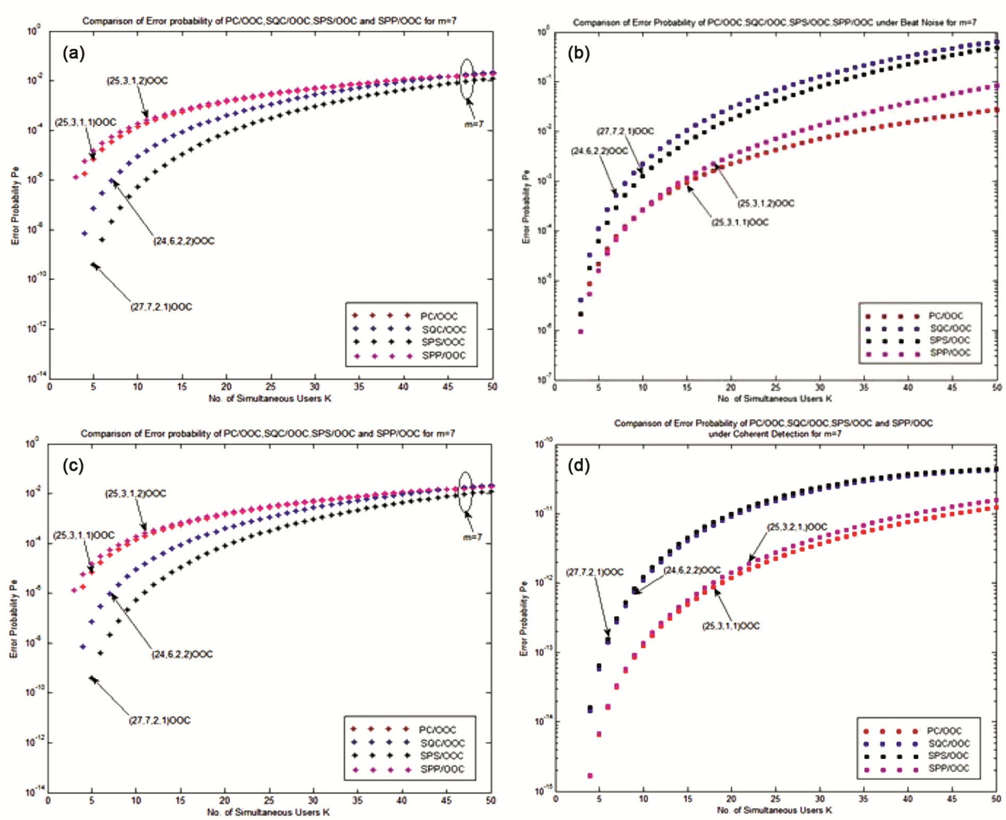

Fig. 2 — (a) Error probability of Codes vs. Number of users for m=7 with MAI, (b) Error probability of Codes vs. Number of users for m=7 with Beat Noise, (c) Error probability of Codes vs. Number of users for m=7 using OHL, (d) Error probability of Codes vs. Number of users for m=7 using Coherent Detection

the graph that for K<23 SPS/OOC performs the best closely followed by SQC/OOC. As the number of users increase beyond 23, SPS/OOC fares the poorest while PC/OOC performs the best. It can be deduced that the code with higher λ_a (=2) performs better for lesser number of users while codes with lower λ_a (=1) performs better when K is increased. Figure 2(b) compares the error probability, from (2.1.1, 2.2.1, 2.3.1 & 2.4.1) for the four codes in the presence of beat noise with respect to number of users at m = 7. It is observed that SPP/OOC and PC/OOC have almost the same error probability for K<15. As K increases, PC/OOC begins to perform better than SPS/OOC. It may be noted that for these codes, the code length and code weight are same, *i.e.* 25 and 3 respectively. The better performance of PC/OOC is, thus, attributed to its correlation properties. Figure 2(c) compares the error probability, from (3.1.1, 1.2.1, 1.2.7 & 1.4.1) for the four codes by using optical hard limiter to combat with noise at m = 7. It is observed that PC/OOC and SPP/OOC have the worst performance as compared to that of SQC/OOC and SPS/OOC. SPS/OOC provides the best performance when K is small, as K increases the performance for all the codes become comparable for m=7. Figure 2(d) compares the error probability, from (4.1.1, 4.2.1, 4.3.1 & 4.4.1) for the four codes by using coherent detection receiver. The graph shows that with coherent detection PC/OOC and SPP/OOC have comparable and the best performance while those of SQC/OOC and SPS/OOC are the worst. Then in Fig. 3, the analysis is made for m = 11 by using the above same equations for probability of error for each code.

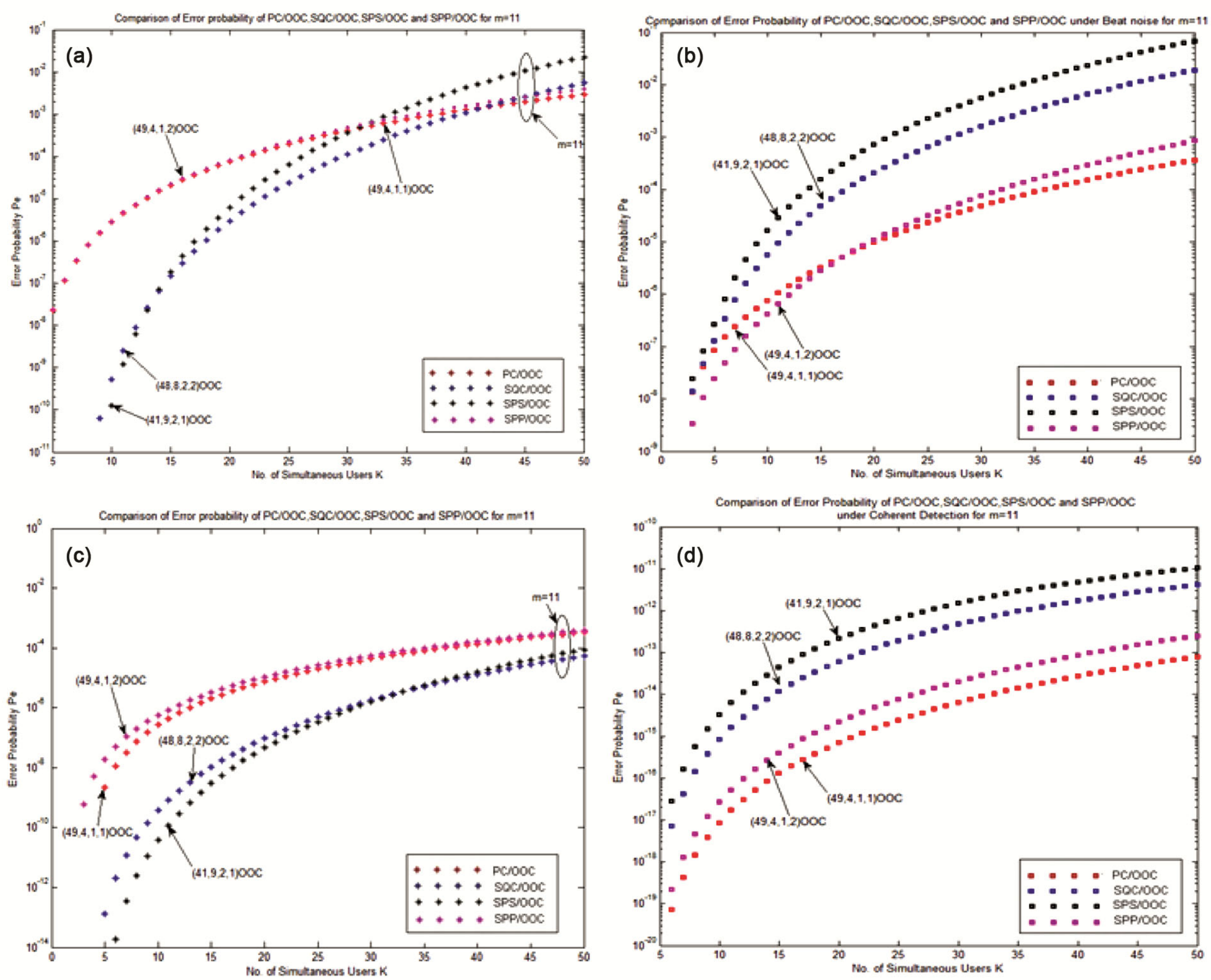

Fig. 3 — (a) Error probability of Codes vs. Number of users for m=11 with MAI, (b) Error probability of Codes vs. Number of users for m=7 with Beat Noise, (c) Error probability of Codes vs. Number of users for m=7 using OHL, (d) Error probability of Codes vs. Number of users for m=7 using Coherent Detection

Figure 3(a) shows that for K <30, SQC/OOC and SPS/OOC have better performance as compared to PC/OOC and SPP/OOC. Beyond K=30, SPS/OOC has the poorest performance while those of the other three codes improve and become comparable. In this case, also, codes with higher λ_c (=2) perform better for lesser value of K. From Fig. 3(b) it is clear that PC/OOC and SPP/OOC show better tolerance to beat noise as compared to SQC/OOC and SPS/OOC.

From Fig. 3(c), it has been observed that PC/OOC and SPP/OOC have near identical performance which is worse than those of SQC/OOC and SPS/OOC. The code weights of SQC/OOC and SPS/OOC are greater than those of PC/OOC and SPP/OOC; this property of heavier code weight improves the error performance when optical hard limiter is used. Fig. 3(d) shows that PC/OOC and SPP/OOC continue to perform better than SPS/OOC and SQC/OOC. Amongst the four codes, PC/OOC performs the best while SPS/OOC performs the worst for coherent detection.

The number of wavelengths is further increased to 13 for more critical analysis of the codes. The results of Fig. 4(a) under the effect of MAI are considerably different from the previous cases for m=7 and 11. For m = 13, SQC/OOC outperforms the others consistently even though its code length is very close to those of others. The ability of SQC/OOC to support a larger code weight is the primary reason for its better performance despite the fact that its λ_a and λ_c are the largest. Its heavier code weight offsets the degradation in code performance for a larger λ_c, thus, providing an overall gain in code performance. Figure 4(b), as m is

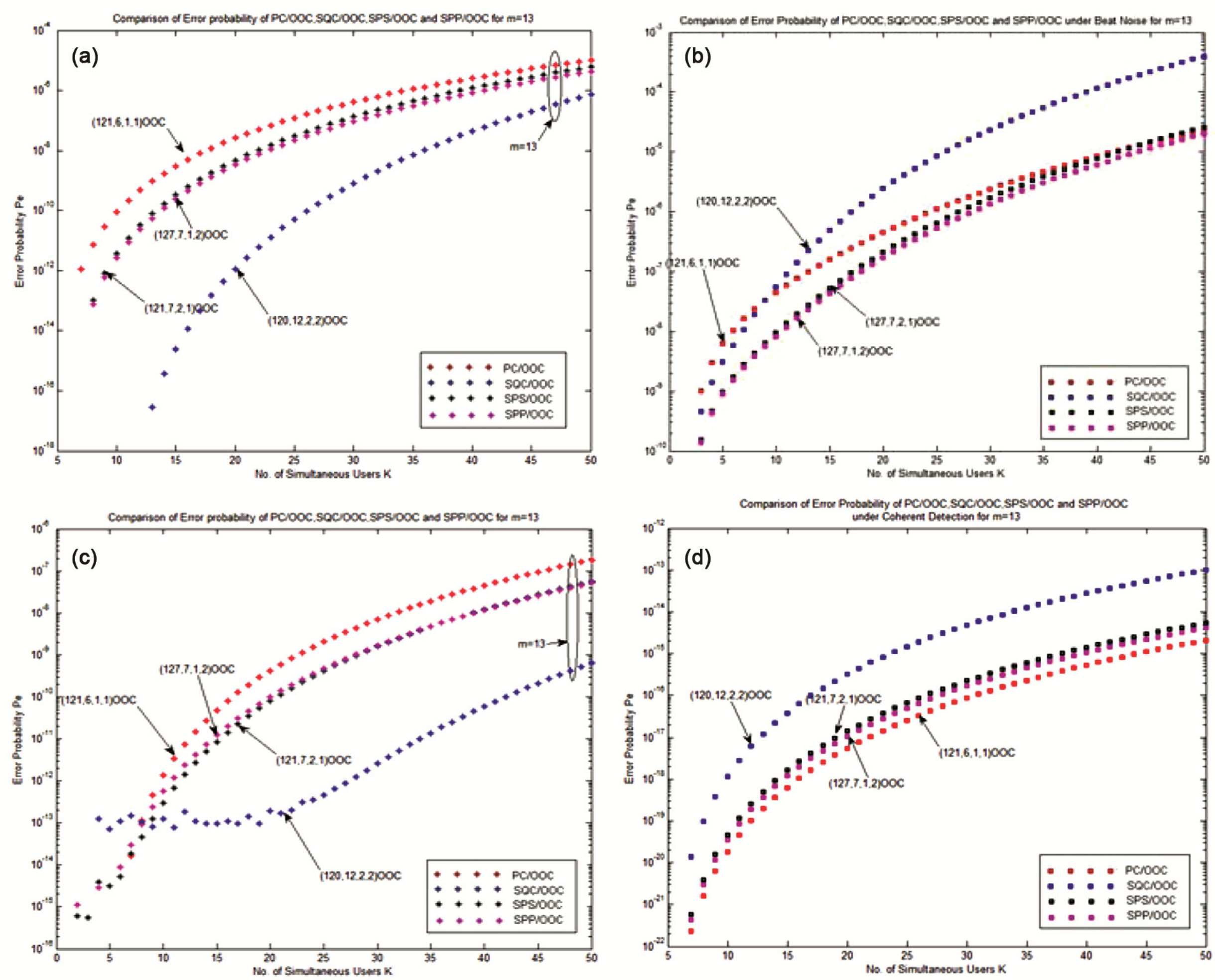

Fig 4 — (a) Error probability of Codes vs. Number of users for m=13 with MAI, (b) Error probability of Codes vs. Number of users for m=13 with Beat Noise, (c) Error probability of Codes vs. Number of users for m=13 using OHL, (d) Error probability of Codes vs. Number of users for m=13 using Coherent Detection further increased to 13, SPS/OOC starts exhibiting better tolerance to beat noise than SQC/OOC and its performance becomes comparable to those to PC/OOC and SPP/OOC.

From Fig. 4(c), it is reported that even though its higher values of λ_a and λ_c should result in poorer code performance, SQC/OOC supports the highest weight (=12) for similar code lengths. Its heavier code weight increases its performance tremendously as compared to the other codes by using optical hard limiter. As shown in Fig. 4(d), SQC/OOC is seen to perform the worst, while the rest of the three codes outperform SQC/OOC with coherent detection.

5 Conclusions

In this paper, an extensive comparative analysis for the four codes SQC/OOC, SPS/OOC, PC/OOC and SPP/OOC is presented under the effect of MAI and Beat noise as well as analysis is made for the effect of using optical hard limiter and coherent detection on these codes by taking different number of wavelengths (m = 7,11 & 13). It has been observed that MAI and beat noise are invetible part of any OCDMA system and seriously degrade the performance of system. OHL and coherent detection both are suitable ways to compensate with noise and there is a noticeable improvement in the code performance as MAI and beat noise are substantially reduced. Investigations reveal that the codes with larger code lengths are best to use when the system is limited by weight of the code. In addition, numerical examples have shown that two combinations that stand out are: SQC/OOC with OHL due to their heavier code weight and PC/OOC with coherent detection due to their lower values of auto- and cross correlation function either can be chosen depending upon the need and limitations of the OCDMA systems.

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