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Comparative Analysis of Optical 2D Codes Using (n, w, λ_a, λ_c) Optical Orthogonal Codes for Optical CDMA

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Abstract—Hybrid two dimensional (2D) wavelength-hopping time-spreading coding techniques have been focused now days for Optical Code Division Multiple Access (OCDMA) systems to increase the capacity of system. In this paper, design and comparative analysis of five different 2D coding techniques has been performed. These codes use Synchronized Quadratic Congruence sequences (SQC), Prime Code sequences (PC), Synchronized Prime Sequences (SPS) and One-Coincidence Frequency Hopping Code (OCFHC) for wavelength hopping and (n, w, λ_a , λ_c) one dimensional optical orthogonal codes for time spreading respectively along with Extended Reed Solomon (E-RS) codes. It has been observed that SQC/OOC code inspite of having larger value of cross correlation than other codes under consideration, out performs due to its ability to support a larger code weight. The comparison on the basis of BER shows that irrespective of the increase in number of hits due to higher code weight, SQC/OOC provides better code performance and hence supports large number of users in the system. The results are reported on the basis of maximum auto- and cross correlation function, cardinality and bit error rate (BER).

Keywords: optical CDMA, optical orthogonal codes, SQC/OOC, PC, SPS, OCFHC, BER

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1. INTRODUCTION

Optical code division multiple access (OCDMA) technique is an extension to CDMA technique in optical domain. It combines the security of CDMA technology with the huge bandwidth of the fiber-optic system to achieve high data rate and security of information transmission. CDMA technology was focused initially for radio frequency communication systems, and was deployed in the field of optical communication in the mid 1980s [1]. Among various multiple access techniques, OCDMA is an interesting subject of research where users share the same transmission bandwidth at the same time by assigning unique optical code to each user [2]. It is supposed to be the best technique for optical communication systems in coming days, especially, for its easy access and increased flexibility in structure; it is used to access the optical networks. In an OCDMA system, first of all, each bit is categorized into n time periods, called chips. Then optical signature sequence is generated by imparting a short optical pulse to the chips, according to the code. Each user in the OCDMA system possess own code set. The bit ‘1’ is denoted by sending the code by transmitter side; however a ‘0’ bit is not encoded and is denoted by zero sequence. So in OCDMA system, each bit is presented as a combination of light and dark (no light) chips, results in increase in bandwidth of the system [1–3]. For the system to be practical, there is a requirement of a coding technique that can be used for large number of users with a low probability of error for a given weight and length of code. As coding techniques represents the base of OCDMA system, various techniques have been proposed and designed by researchers: one dimensional (1D) codes that can be represented either in time or frequency domain. Generally we use temporal coding means coding in time domain, by sending very short optical pulse for bit ‘1’. The number of users in 1D code is proportional to length of the code that in turn is dependent upon width of the optical pulse used so the number of users in one dimensional coding is always limited [4]. To overcome the limitation of one dimensional coding, two dimensional (2D) coding techniques are performed by introducing another dimension (wavelength) by various researchers to enhance the capacity of the system. Many two dimensional wavelength-hopping time-spreading (WH/TS) codes have been designed by using different wavelength hopping and time spreading patterns. In general, a family of 2D optical code C is represented by (n, w, λ_a, λ_c) , where n denotes the length of sequence, w denotes the code weight, λ_a represents auto-correlation side lobes and λ_c denotes the cross-correlation function. Any set of 2D codes is designed to satisfy the following properties [5], [12]:

(i) Auto-Correlation Property

$$\sum_{i=0}^{m-1}\sum_{j=0}^{n-1} x_{i,j}\, x_{i,j\oplus\tau} \le \lambda_a. \tag{1}$$

For all $x \in c$ and any integer τ, $0 \le \tau \le n-1$

(ii) Cross-Correlation Property

$$\sum_{i=0}^{m-1}\sum_{j=0}^{n-1} x_{i,j}\, y_{i,j\oplus\tau} \le \lambda_c. \tag{2}$$

For $x \ne y \in c$ and any integer τ, $0 \le \tau \le n-1$, "$\oplus$" represents modulo n-addition.

A two dimensional OOC designed by using prime sequences for wavelength hopping as well as for time spreading (PC/PC) algorithms was demonstrated in [6], but poor cardinality limited the number of subscribers in the system. T. Srinivas et al. [7] designed extended quadratic congruence code for wavelength hopping and prime codes for time spreading (EQC/PC) with a large value of cardinality but these codes possess poor correlation properties. In [8], multiple wavelength optical orthogonal codes (MWOOCs) are demonstrated by using one dimensional orthogonal codes for time spreading and prime sequence for wavelength hopping (PC/OOC). These codes were constructed by using the value of $\lambda_c = 1$ to mitigate the effect of multiple access interference. Then Yang et al. [9] suggested larger cardinality by using wavelength time codes by relaxing the maximum value of cross-correlation functions to two (i.e $\lambda_c = 2$). To further enhance the cardinality, Wang et al. [10] changed the time spreading (n, w, 2, 1) 1D OOCs with (n, w, 1, 2) OOCs. In [11], Salehi et al. calculated the best permissible values of the weight and maximum cross correlation λ_c of code that can lesser down the probability of error. Taking into consideration all the facts above, design and comparative analysis of five coding techniques SQC/OOC, PC/OOC, SPS/OOC, OCFHC/OOC and E-RS has been done in this paper to obtain larger cardinality that is maximum number of subscribers and good auto-, cross correlation properties in the system. These five coding techniques are compared on the basis of different parameters like maximum auto correlation side lobes, cross correlation, cardinality and BER under certain conditions.

The rest part of this paper is organized in following manner. The construction and the properties for various codes considered are studied in section 2. Further, section 3 substantiates the analysis by providing numerical examples for comparison of these codes on the basis of different parameters in section 3. Finally section 4 concludes the paper.

2. CONSTRUCTION AND PROPERTIES OF CODES

A brief overview of the construction and important properties of the selected codes is presented in this section one after the other.

2.1. SQC/OOC

This family of 2D codes uses synchronized quadratic congruence sequences as the wavelength hopping code whereas (n, w, 2, 2) optical orthogonal codes are used as the time spreading code [9]. The construction of code begins with taking a (n, w, 2, 2) 1D OOCs of length n as the time spreading codes and then the wavelength hopping is algebraically done by quadratic congruence sequences [8]. The synchronized QC sequences are derived by choosing p as a prime number that is based on the Galois field. The sequence is described as follows [9]:

$$S_{a,\alpha,\beta} = (S_{a,\alpha,\beta}(0), S_{a,\alpha,\beta}(1), \ldots\ldots. S_{a,\alpha,\beta}(k) \ldots.. S_{a,\alpha,\beta}(P-1)). \tag{3}$$

Here $a \in \mathrm{GF}(P)\backslash 0 = \{1, 2, \ldots\ldots., P-1\}$ and $\alpha, \beta \in \mathrm{GF}(P) = \{1, 2, \ldots\ldots., P-1\}$.

The various codes of this quadratic congruence sequence are derived by:

$$S_{a,\alpha,\beta}(k) = \left\{a\left(k+\alpha\right)^2 + \beta\right\}(\bmod P),\ \ k = 0, 1, 2, \ldots, P-1. \tag{4}$$

While varying the parameters a, α and β, p groups of p^2 sequences are formed, that results in a p^3 synchronized QC sequences. Thus taking these sequences as wavelength hopping patterns, p^3 permutations are obtained for controlling the wavelengths in each of the time spreading codes.

A. Correlation Properties:

The correlation properties of SQC/OOC coding technique are linked with wavelength hopping synchronized QC sequences and time spreading (n, w, 2, 2) 1D OOCs. Hence the autocorrelation and cross correlation values of SQC/OOC are both 2.

B. Cardinality:

As the value of $\lambda_a = \lambda_c = 2$, so number of wavelengths should be greater than or equal to weight of the code. The cardinality of the code is described as follows [9]:

$$\varnothing_{2D} = \varnothing_{(n,w,2,2)\mathrm{OOC}}\varnothing_{\mathrm{group}} \leq \varnothing_{(n,w,2,2)\mathrm{OOC}}P^3. \tag{5}$$

Here $\varnothing_{\mathrm{group}} \leq P^3$ denotes the number of synchronized QC sequences.

C. Hard Error Probability:

Let q_2^0 and q_2^1 be the probability of having two hits, when the desired code set correlates with the interfering code set from sequences of subgroup ($g = 0$, $i_1 = 0$) and other subgroups respectively. Taking q_i as the probability in a given time slot possessing cross correlation function of i, then from [9]:

$$q_2 = \frac{1}{p}q_2^0 + \frac{p^2-1}{p^2}q_2^1, \tag{6}$$

$$q_0 + q_1 + q_2 = 1, \tag{7}$$

$$q_1 = \frac{w^2}{2P_n} - 2q_2. \tag{8}$$

The hard limiting error of probability is described by [9]:

$$P_e \leq \frac{1}{2}\sum_{i=0}^{w}(-1)^i\binom{w}{i}\left[q_0 + \frac{q_1(w-i)}{w} + \frac{q_2(w-i)(w-i-1)}{w(w-1)}\right]^{k-1}. \tag{9}$$

In the above description k stands for the number of users in the system.

2.2. PC/OOC

This family of codes supports multiple wavelength hopping for a given time spreading code by using prime sequences for wavelength hopping and (n, w, 1, 1)optical code for time spreading. The time slot may contain none or one pulse of the appropriate wavelength in this code [8]. This wavelength is decided with the help of permutations of wavelengths done by the prime sequences over non-zero time slots of the predecided time spreading orthogonal code. The code weight w of optical orthogonal codes can be as high as p (the prime number).

A. Correlation Properties:

The value of auto correlation and cross correlation functions of the PC/OOC codes is 1 to minimize the effect of multiple access interference MAI.

B. Cardinality:

The cardinality of optical orthogonal codes is described by [8]:

$$\varnothing_{\mathrm{OOC}} \le \frac{N_{\mathrm{OOC}} - 1}{w(w-1)}. \quad (10)$$

Here $N_{\mathrm{OOC}} \ge w(w-1)\varnothing_{\mathrm{OOC}} + 1$ denotes the code length and w denotes the code weight. The cardinality of PC/OOC is described by [6]:

$$\varnothing_{\mathrm{PC/OOC}} = \varnothing^{*}_{\mathrm{OOC}} P^2. \quad (11)$$

C. Hard Error Probability:

Let q^0 and q^i be the probability of having one hit among the code set from group 0 and group i (for i = 1, 2, ... $p - 1$), respectively. Then we have from [8]:

$$q^0 = \frac{w^2(\varnothing_{\mathrm{OOC}} - 1)}{2N_{\mathrm{OOC}}\left(\varnothing_{\mathrm{OOC}*P^2} - 1\right)}, \quad (12)$$

$$q^i = \frac{w^2(\varnothing_{\mathrm{OOC}p} - 1) + (w-1)^2}{2N_{\mathrm{OOC}}\left(\varnothing_{\mathrm{OOC}*P^3} - 1\right)}. \quad (13)$$

Taking Th and k as the decision threshold and number of users in the system respectively, the probability of error in case of PC/OOC is given by [6]:

$$P_e \le \frac{1}{2}\sum_{i=0}^{Th}(-1)^i\binom{w}{i}\left[1 - \frac{q_i}{w}\right]^{k-1}. \quad (14)$$

In general, for the optimum performance of the system the value of decision threshold is taken to be equal to the weight of the code.

2.3. SPS/OOC

This family of 2D codes utilizes wavelength hopping done by permutations of synchronized prime sequences over a chosen time spreading (OOC) code. These codes, first of all, are designed by taking a (n, w, 2, 1) 1D OOC of length n as the time spreading code. After that, wavelengths are assigned to the pulses of time spreading OOC for wavelength hopping. The synchronized prime sequences over Galois field GF (p) are obtained from [12] as:

$$S_{i,j} = (S_{i,j,1}, S_{i,j,2}, \ldots\ldots S_{i,j,l} \ldots\ldots S_{i,j,p-1}), \quad (15)$$

$$S_{i,j,l} = (i \otimes l) \oplus j. \quad (16)$$

Here j, i and l are in Galois field, which is a prime number, "⊗" represents a modulo- multiplication, and "⊕" represents a modulo- addition. The synchronized prime sequences are generated in p groups, started by i [3]. Every prime sequence having the value of $j = 0$ is used to start other sequences in group, results in synchronized prime sequences. This provides p^2 permutations for providing wavelengths to the pulses of the time spreading optical orthogonal codes.

A. Correlation Properties:

This code possesses a unique cross correlation property as the value of cross correlation function changes with the group number. If the two codes belong to the same group, then the value of cross correlation is two and if they belong to different groups then their cross correlation value is one.

B. Cardinality:

The cardinality of SPS/OOCs is described by $\varnothing_{(n,w,2,1)} P^2$ [12] where

$$\varnothing_{(n,w,2,1)\mathrm{OOC}} = \begin{cases} \dfrac{2(n-1)}{w^2-1}, & \text{for odd value of } w \\ \dfrac{2(n-1)}{w^2}, & \text{for even values of } w \end{cases}. \tag{17}$$

C. Hard Error Probability:

Let q_1^0 and q_1^i denote the probability of having one hit in a time slot for desired code set from group 0 and i. Also let q_2^i be the probability of having two hits in the cross correlation where $i = \{1, 2, ... p-1\}$; then for odd values of weight,

$$q_2^i = \frac{(w-1)^2}{4N\left(\varnothing_{(n,w,2,1)\mathrm{OOC}P^2} - 1\right)}. \tag{18}$$

And for even values of weight

$$q_2^i = \frac{w(w-2)}{4N\left(\varnothing_{(n,w,2,1)\mathrm{OOC}P^2} - 1\right)}. \tag{19}$$

The hard error probability of SPS/OOC can be given by [12]:

$$P_e \le \frac{1}{2}\sum_{i=0}^{w}(-1)^i \binom{w}{i}\left[q_{2,0} + \frac{q_{2,1}(w-i)}{w} + \frac{q_{2,2}(w-i)(w-i-1)}{w(w-1)}\right]^{k-1}. \tag{20}$$

Here k stands for the number of users in the system.

2.4. OCFHC/OOC

For wavelength hopping this family of 2D codes uses one-coincidence frequency hop code and for time spreading it makes use of optical orthogonal codes. Frequency hop code (FHC) can be defined as a set of different code words that determines how the carrier frequencies or wavelengths should be placed in different time slots depending upon some parameters like available frequencies Q, length and cardinality of code, and the highest value of correlation function among two codes [13]. A code word is denoted as $(p^k xN_{\mathrm{OOC}}, w, \lambda_a, \lambda_c)$ where p^k stands for the available wavelengths and N_{OOC} represents the code length. The value of auto- and cross correlation function is at most equal to 1.

A. Correlation Properties:

In accordance with the property of orthogonal optical codes, the maximum permissible value of autocorrelation of any code set belongs to OCFHC/OOC is equal to 1.

B. Cardinality:

The cardinality of this code is given by [13]:

$$\varnothing_c = \varnothing_{c0} + \varnothing_{c1} + \varnothing_{c2} = \frac{p^{2k}(N_{\mathrm{OOC}} - p^k)}{w(w-1)}. \tag{21}$$

Where $\varnothing_{c0}$, $\varnothing_{c1}$ & $\varnothing_{c2}$ are the cardinalities of c_0, c_1 & c_2 respectively.

$$\varnothing_{c0} = p^k \left(p^k - 1\right) \frac{(N_{\text{OOC}} - 1)}{w(w-1)}, \tag{22}$$

$$\varnothing_{c1} = p^k \frac{(N_{\text{OOC}} - 1)}{w(w-1)}, \tag{23}$$

$$\varnothing_{c2} = \frac{p^k \left(p^k - 1\right)}{w(w-1)}. \tag{24}$$

C. Hard Error Probability:

The equation of probability of error for OCFHCPS/OOC is given by [13]:

$$P_e \le \frac{1}{2} \sum_{i=0}^{k-1} \binom{k-1}{i} (q)^i [1-q]^{k-1-i}. \tag{25}$$

Here k denotes the number of users in the system.

2.5. E-RS

This family of 2D optical codes is based on extended RS codes. These codes are derived from Reed Solomon codes by modifying the general polynomials of RS codes. These codes are algebraically generated over Galois field GF (p). These codes have length equal to prime number (p), but the number of wavelengths and weight both are equal to $p + 1$. These codes are obtained by direct mapping of the code-coefficients of some code set to the available wavelengths and time slots [14].

A. Correlation Properties:

As each of the code set in E-RS codes carries at most one pulse per wavelength so the value of cross correlation function will not get worsened with dropping pulses. For any two sets taken randomly from different groups, the value of cross correlation function is as high as $p + 1$.

B. Cardinality:

Each code set in E-RS code is denoted by ($p + 1$, k, $p - k + 2$) where length of code is $p + 1$, maximum value of cross correlation is $k - 1$ and minimum hamming distance is $p - k + 2$. The value of $k \ge 1$ is odd and is dimension of code. The overall cardinality of E-RS coding technique is described by p^k.

C. Hard Error Probability:

The error probability for E-RS code using combinational analysis is given by [14]:

$$P_e \le \frac{1}{2} \sum_{i=0}^{Th} (-1)^i \binom{w}{i} \left[\sum_{j=0}^{\lambda_c} q_{\lambda_c, j} \frac{\binom{w-i}{j}}{\binom{w}{j}} \right]^{k-1}. \tag{26}$$

In the above equation, k stands for the number of users and $q_{\lambda c, j}$ represents the probability of having j= {0, 1, 2.......λ_c} hits in single time slot.

3. COMPARATIVE ANALYSIS

In this section the five codes are compared on the basis of different parameters like auto- and cross correlation values, cardinality and hard error probability.

Table 1. Codes with auto- and cross correlation values

Code type	Maximum auto correlation λ_a	Maximum cross correlation λ_c
SQC/OOC	2	2
PC/OOC	1	1
SPS/OOC	2	2
OCFHC/OOC	1	1
E-RS	0	Variable

3.1. Comparison of Codes on the Basis of Auto- and Cross Correlation

In general, most of the 2D codes are generated by taking the maximum value of cross correlation ($\lambda_c = 1$) equal to 1, to mitigate the effect of multiple access interference. But it is reported by various authors [7], that the larger cardinality can be obtained by increasing the value of cross correlation function. Table 1 below compares the codes with maximum value of auto and cross correlation.

Form the table, we see that λ_c for SQC/OOC is higher; it outperforms the other codes because the heavier code weight supported by larger value of λ_c helps to compensate for the degradation in performance. Figure 1 demonstrates the maximum auto-correlation side lobe λ_a by using the concept of matched filter [9]. The user data is taken as 1101. Codes have been chosen randomly for comparison purpose. Any two codes from the same group 0 and one code from another group is taken. It is clear from the figure, that in all, the three cases, the maximum auto correlation side lobe λ_a is at most 2. However, the peak auto-correlation value is 5, and is equivalent to the code weight. Similarly figure 2 demonstrates maximum cross correlation function λ_c for the same user data and codes. It is clear from the graph, that for codes belonging to same group, the maximum cross correlation is at most 2 and for the codes belonging to different groups the maximum cross correlation value is 0.

3.2. Comparison of Codes on the Basis of Cardinality

From the table, it is clear that for any value of given prime number p, the cardinality of SQC/OOC is far greater than that of PC/OOC and SPS/OOC. For E-RS code, cardinality is given by $p^{\lambda c}$, where λ_c is the maximum cross correlation. For comparison purpose, we take λ_c =2 in this case also. Thus the cardinality of SQC/OOC is greater than that of E-RS for same value of λ_c.

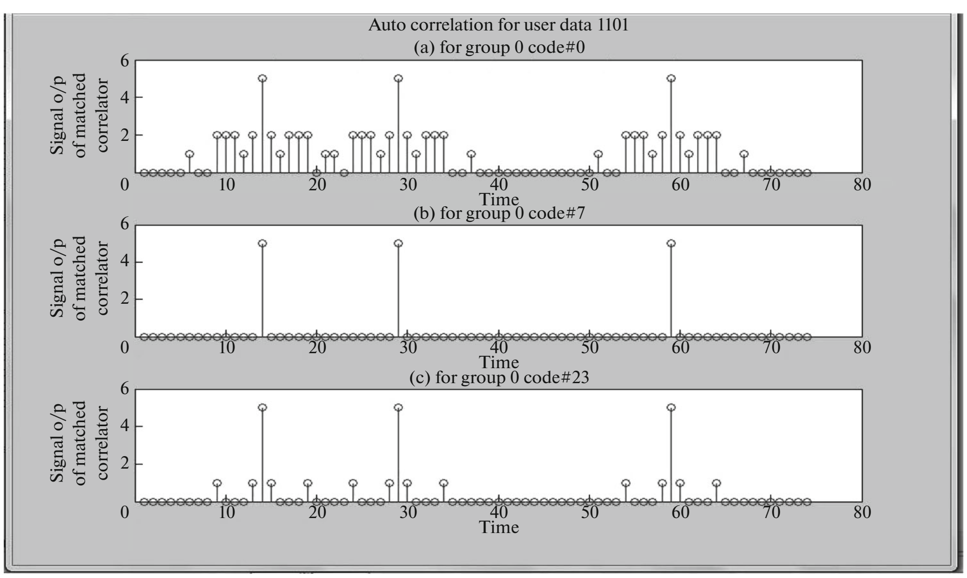

Fig. 1. Demonstration of Maximum Auto correlation side lobes λ_a.

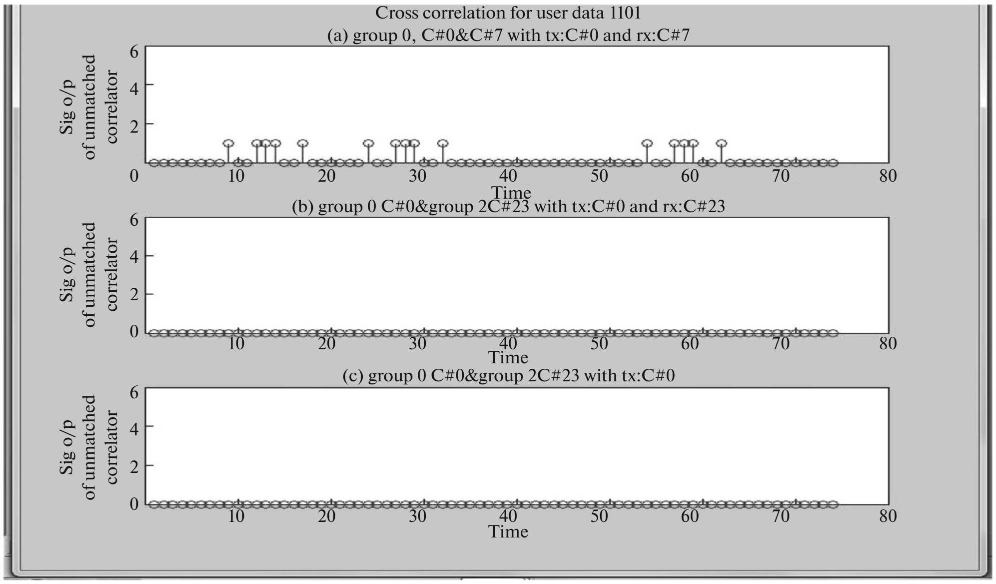

Fig. 2. Demonstration of Maximum Cross correlation function λ_c.

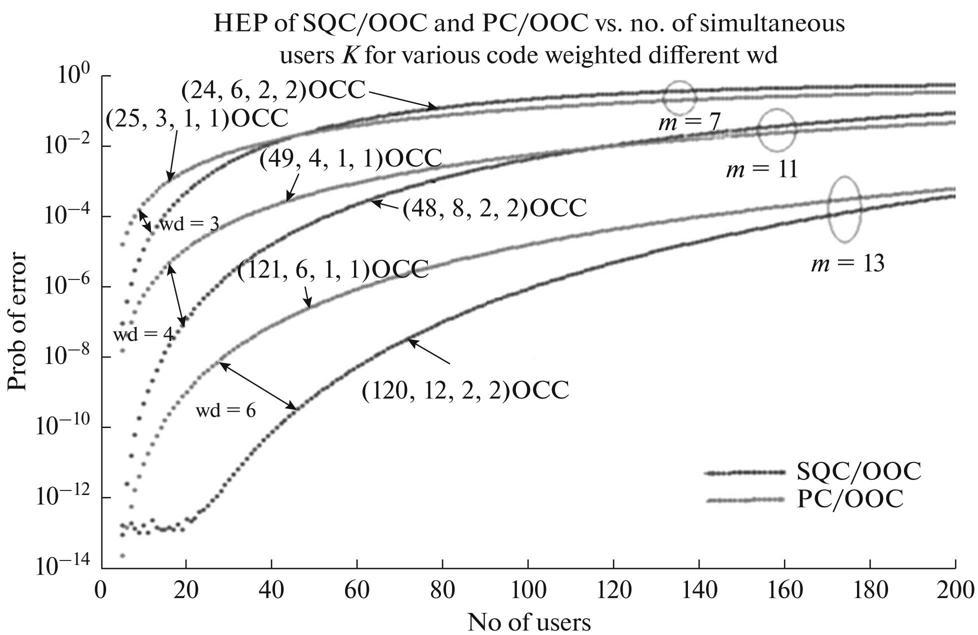

Fig. 3. Comparison of SQC/OOC and PC/OOC.

3.3. Comparison of Codes on the Basis of Probability of Error

A.SQC/OOC versus PC/OOC:

Figure 3 compares the probability of error of $\lambda_c = 2$, SQC/OOC codes using equation (1.7), that are based upon (n, w, 2, 2) time spreading orthogonal codes [i.e., (9)] with PC/OOC codes that are based upon (n, w, 1, 1) time spreading orthogonal codes using equation (2.5) [i.e, (6)] versus number of simultaneous users. The curves are plotted by taking various values of length of code n, weight w and the number of wavelengths. For same code weight, performance of SQC/OOC should be worse in comparison to PC/OOC as the value of λ_c is equal to 2 in case of this code. However, the larger weight supported by SQC/OOC for the same value of length of code and wavelengths and the larger code cardinality results in

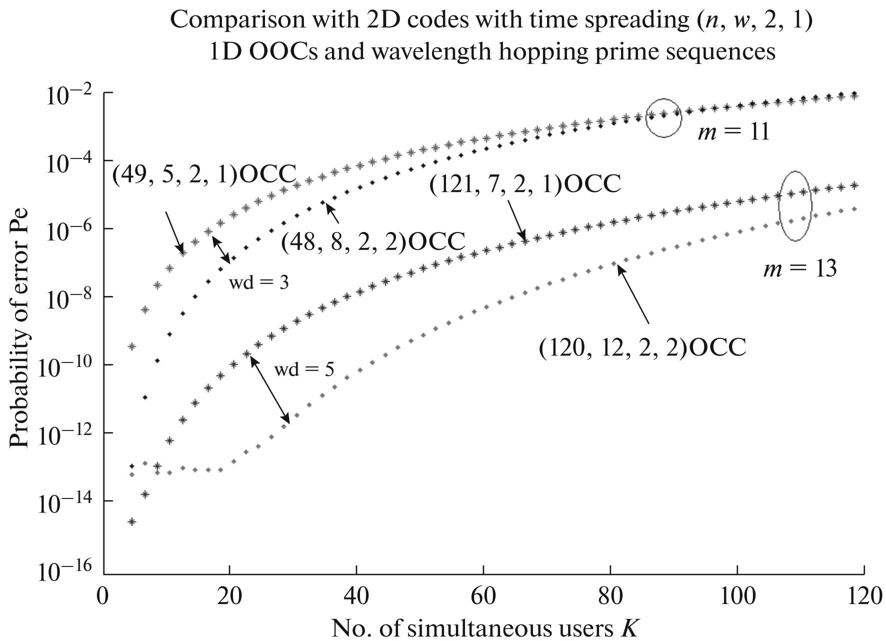

Fig. 4. Comparison of SQC/OOC and SPS/OOCs.

a better performance of SQC/OOC. For example, SQC/OOC generated by (120, 12, 2, 2) OOC has w = 12, while the PC/OOC generated by (121, 6, 1, 1) OOC has w = 6. It has been observed from the plot that difference in performance increases with difference in weight.

B.SQC/OOC versus SPS/OOC:

Figure 4 shows the comparison of error probability versus number of users simultaneously accessing the network for SQC/OOC [9] using equation (1.7) and SPS/OOC [12] coding techniques using equation (3.6) that are based upon (n, w, 2, 2) time spreading optical orthogonal codes. Again the graphs are plotted for different values of length, weight of code and the number of wavelengths $m = p$. In general, for same values of n, w and m both these codes should possess almost same performance as they both have $\lambda_\alpha = 2$. However, SQC/OOC supports a larger weight as compare to SPS/OOC for example, for the same number of wavelengths m = 13, the code generated by SQC/OOC (120, 12, 2, 2) has value of w = 12 and is equal to 7 for the code generated by SPS/OOC. Thus SQC/OOC has a superior performance.

C.SQC/OOC versus OCFHC/OOC:

Figure 5 shows the comparison of probability of error for SQC/OOC coding technique, based upon the (n, w, 2, 2) time spreading orthogonal codes [i.e., (9)] using equation (1.7) with OCFHC/OOC codes based upon (n, w, 1, 1) time spreading codes [i.e, (14)] using equation (4.5) versus number of simultaneous users. The curves are plotted by taking various values of weight, length of code and by taking number of wavelengths. From the plots, it is clear that for the same values of wavelength $m = p$, SQC/OOC performs very well as compare to OCFHC/OOC. Even for the same value of code weight, w = 11, the probability

Table 2. Below shows the codes and their cardinality taken for analysis

Wavelength hopping code	Time spreading code	2D code	Cardinality $\varnothing_{2D}$
SQC	OOC	(n, w, 2, 2)	$\varnothing^3_{(n,w,2,2)p}$
PC	OOC	(n, w, 1, 1)	$\varnothing^2_{(n,w,1,1)p}$
SPS	OOC	(n, w, 2, 1)	$\varnothing^2_{(n,w,2,1)p}$

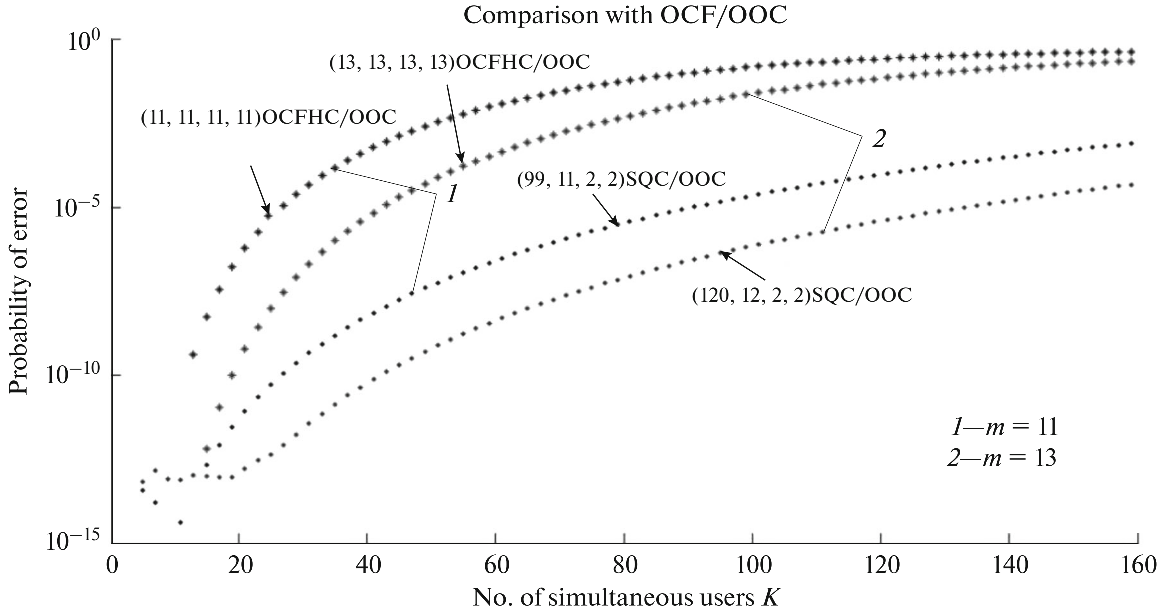

Fig. 5. Comparison of SQC/OOC and OCFHC/OOCs.

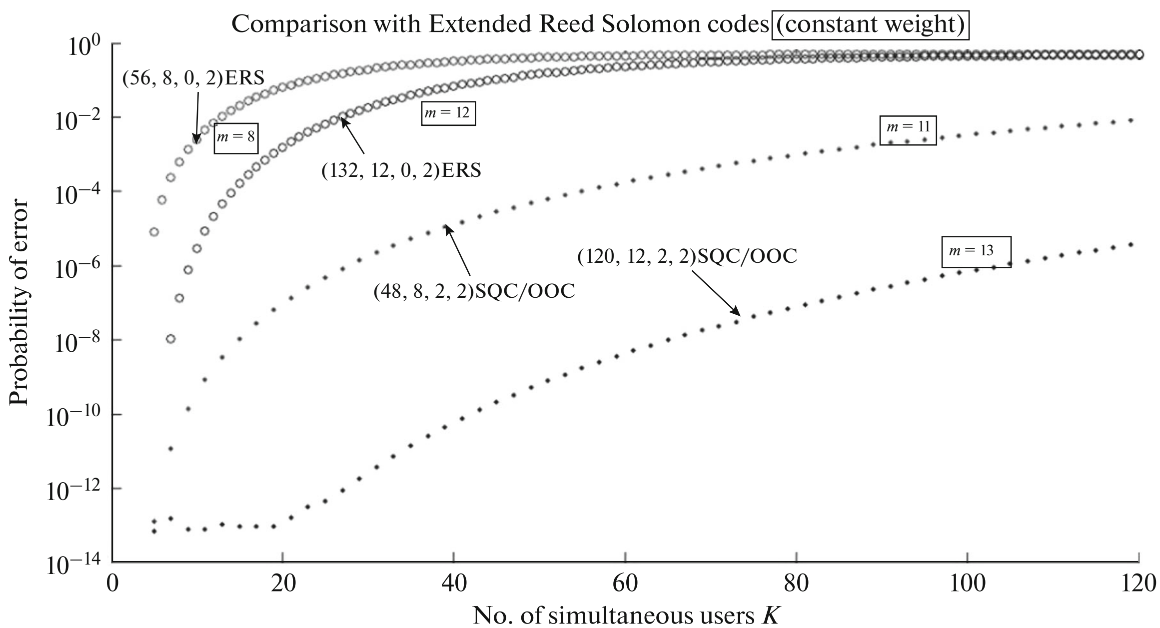

Fig. 6. Comparison of SQC/OOC and ERS Codes.

of error for SQC/OOC is less in comparison to OCFHC/OOC that further proves the optimum performance of SQC/OOC codes. Hence, for the same weight of the code also, SQC/OOC coding scheme is better.

D.SQC/OOC versus E-RS:

Figure 6 compares the probability of error of $\lambda_c = 2$, SQC/OOC scheme, based upon the (n, w, 2, 2) time spreading codes [i.e., (9)] using equation (1.7) with extended Reed-Solomon codes [14] using equation (5.1) versus number of simultaneous users. The curves are plotted by taking various values of length of code n, number of wavelengths and weight. From the graph, it is clear that for the same value of wavelength $m = p$ and for same code weight SQC/OOC again takes an edge in comparison to E-RS code.

4. CONCLUSIONS

In this paper, five codes SQC/OOC, SPS/OOC, PC/OOC, OCFHC/OOC and E-RS are designed and compared in order to obtain good auto- , cross correlation properties as well as to obtain higher cardinality for optical CDMA systems. Our results have shown that SQC/OOC gives better performance in comparison to all the other codes for various performance metrics like cardinality, auto- and cross correlation values and probability of error. In addition, the numerical examples have shown that increase in weight of code and large cardinality of the code compensates for degradation in performance due to $\lambda_c = 2$. Hence provides a net gain in performance. Therefore, SQC/OOC codes are best suited for the OCDMA systems supporting large number of simultaneous users accessing the system in comparison to other 2D codes.

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