QUALITY OF SERVICE DIFFERENTIATION IN MULTIMEDIA 2D OPTICAL CDMA NETWORKS

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ABSTRACT

The incoherent Optical Code Division Multiple Access (OCDMA) is studied as a potential asynchronous access technique for multimedia applications. In this paper, we propose to provide multi-service applications with 2D codes based on Optical Orthogonal Code (OOC) namely: Multi-Wavelength Optical Orthogonal Code (MWOOC). The Quality of Service (QoS) differentiation is realized by partitioning a 2D code set into matrices with different weights. We develop the theoretical error probability expression of such system in the noiseless case with a Conventional Correlation Receiver (CCR). This permits evaluating the performance in the case of multimedia application.

1. INTRODUCTION

Code Division Multiple Access (CDMA) is a spread spectrum technique well developed in the world of radio communications systems. The technique consists in allocating to each user a specific and distinct code sequence to access the communication network. In the optical world, CDMA has been suggested as a possible technology for high-speed Local Area Networks (LAN) [1]. Indeed, for the uplink stream of a Passive Optical Network (PON), it has been shown that users can share the communication bandwidth more effectively by using Optical CDMA [2].

Besides, it is expected that future access networks will support various multimedia applications (data, voice and video). These services need to be transmitted at different data rates and do not require the same Bit Error Rate (BER) i.e. the same Quality of Services (QoS). The QoS depends on the coding method used.

Different OCDMA coding methods have been proposed. The oldest solutions deal with spreading codes in one dimension (1D): temporal [3] or spectral [4]. More recent coding schemes using both wavelength and time spreading simultaneously (2D) have been proposed [5-8].

In a single-service OCDMA system, the QoS can be improved either by increasing the code length or the code weight. In a multi-service system, the code weight is the main parameter to provide QoS differentiation. As the BER is weight-dependent, one can consider that low code weight (respectively high code weight) will be associated to low QoS (resp. high QoS) requirements.

Many works on multi-weight OCDMA for QoS differentiation have already been investigated [9-13]. Most of these works are based on 1D coding method [9-12]. Some construction schemes have been proposed to generate 1D multi-weight codes based on Pairwise Balanced Design (PBD) or Optical Orthogonal Codes (OOC) [9-12]. In [11] the authors propose a packing design method to partition a 1D constant weight code into subcodes with a smaller weight, for two services differentiation.

However, the use of 1D code leads to several drawbacks. Indeed, the low cardinality of 1D code limits the number of users in the network. Moreover, to overcome the Multiple Access Interference (MAI) impact, 1D code length has to be high enough and thus, limits the data rate.

On the contrary, 2D coding methods allow higher number of users and provide better performance at higher data rates. One published work based on a 2D OCDMA system proposes a double-weight coding method [13] to support only two services differentiation.

In this paper, we propose a partitioning method applied to 2D codes in order to perform more than two services differentiation. From 2D codes named Multi-Wavelength Optical Orthogonal Codes (MWOOC), which provide a single-service with high QoS, i.e. low BER, we define 2D subcodes with lower weights values for different BER values. The correlation properties of the 2D subcodes are maintained and a theoretical analysis of the error probability of each 2D code set is developed.

The paper is organized as follows. In section 2, the 2D-OCDMA system is described. In section 3, the partitioning method of MWOOCs is presented. The theoretical error probability for S services is developed in section 4 when a conventional single user receiver is used. Then, we study in section 5, the performance of the multi-weight 2D codes in the case of three services differentiation.

2. SYSTEM DESCRIPTION

We consider an asynchronous incoherent OCDMA system using 2D codes. Each user employs an On/Off Keying (OOK) modulation to transmit independent and equiprobable binary data upon an optical channel. A 2D code can be represented by a matrix of dimension ($m \times n$), where m and n are related respectively to the spectral and the temporal spreading.

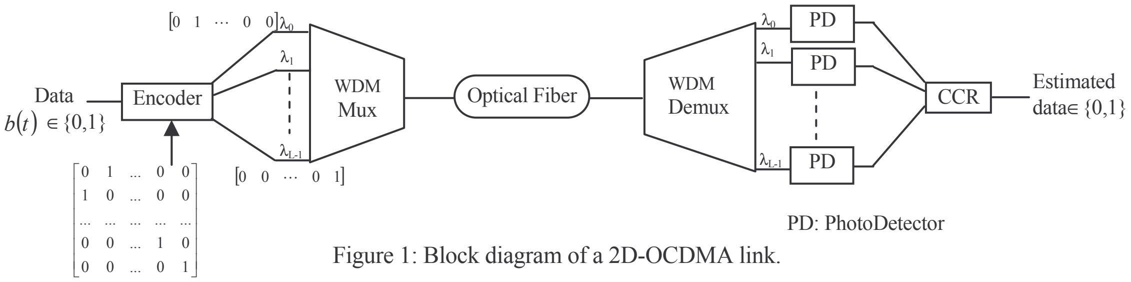

Figure 1: Block diagram of a 2D-OCDMA link.

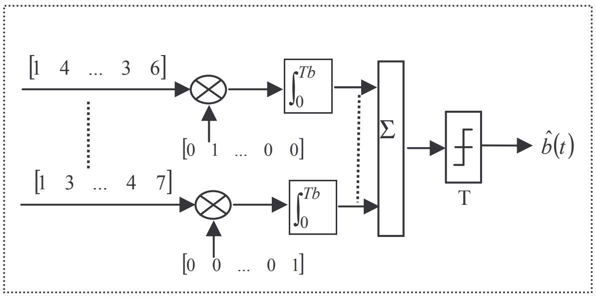

Figure 2: Conventional Correlation Receiver (CCR) scheme.

$$\begin{bmatrix} 1&0&0&0&0&0&0&0&0\\ 0&1&0&0&0&0&0&0&0\\ 0&0&0&1&0&0&0&0&0\\ 0&0&0&0&0&0&1&0&0\\ 0&0&0&0&1&0&0&0&0\\ 0&0&0&0&0&1&0&0&0\\ 0&0&0&0&0&0&0&1&0\\ 0&0&1&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&1 \end{bmatrix} = \begin{bmatrix} &&&&&&&&\\ &&&&&&&&\\ &&&&&&&&\\ 0&0&0&0&0&0&1&0&0\\ 0&0&0&0&1&0&0&0&0\\ 0&0&0&0&0&1&0&0&0\\ 0&0&0&0&0&0&0&1&0\\ 0&0&1&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&1 \end{bmatrix} + \begin{bmatrix} 1&0&0&0&0&0&0&0&0\\ 0&1&0&0&0&0&0&0&0\\ 0&0&0&1&0&0&0&0&0\\ &&&&&&&&\\ &&&&&&&&\\ &&&&&&&&\\ &&&&&&&&\\ &&&&&&&&\\ &&&&&&&& \end{bmatrix}$$

$$C^k \quad = \quad C_1^k \quad + \quad C_2^k$$

Figure 3: Example of matrix partition with m=2, L=9, L_1=6 and L_2=3.

It is defined by: $(L\times F, W, h_a, h_c)$ where L is the number of wavelengths for spectral spreading, F is the temporal code length (the bit period is subdivided in F intervals called chips), W is the weight corresponding to the number of chips set to one, h_a and h_c are the auto and cross-correlation values. The L and F values are chosen as low as possible in order to minimize the impact of beat interference and to maximize the data rate.

Figure 1 shows a block diagram of the 2D-OCDMA link. Data are encoded by the user code matrix, and then each matrix row is emitted at a different wavelength λ_i. The wavelengths are multiplexed before being transmitted through the fiber. At the end line, after demultiplexing the wavelengths, we consider a Conventional Correlation Receiver (CCR) (figure 2). After correlation with the desired user code matrix, we get the decision variable value which is compared to the threshold level T of the decision device to provide an estimation of the transmitted data.

3. MULTI-WEIGHT MWOOC CONSTRUCTION

To generate code families with constant length and different weight values, we first construct a single service 2D code family with parameters ($L\times F$, W, 1, 1), named MWOOC [8].

3.1 MWOOC($L\times F$,W=L) construction

The construction of a MWOOC matrix is based on a 1D code. We use vectors from the family called Optical Orthogonal Codes, OOC (F, W, h_a, h_c) [1,3] with correlation values set to one (h_a=h_c=1).

To construct 2D codes, we impose the temporal code length value F to be a prime number. Moreover, since there is at most one chip set to one per wavelength, the minimal number of wavelengths we can obtain is equal to the weight: L=W.

Let $[a_0, a_1, \ldots, a_{w-1}]$ be the used OOC(F, W=L, 1, 1) position vector. The a_i values are the position of chip pulses set to '1' in the 1D code sequence.

From this vector, the '1' positions in the 2D code matrices are constructed according (1):

$$C^j = \{[0, a_0\times j], [1, a_1\times j], \ldots, [L-1, a_{L-1}\times j]\} \qquad (1)$$

$$C^{F+i} = \{[i, a_0], [i, a_1], \ldots, [i, a_{L-1}]\}$$

where i ∈ [0, L-1] is related to the transmitted wavelength and j ∈ [0, F-1] is related to the temporal chip position. The product $a_i\times j$ is a modulo-F multiplication. This construction method provides a maximum number of users N:

$$N = L + F \qquad (2)$$

Let $C = \{C^k\}$ be the set of constructed matrices, with k ∈ [0, N-1].

3.2 Multi-Weight code generation

3.2.1 *Principle*

The main idea to generate Multi-Weight MWOOC is to split the matrices ($L\times F$) into several matrices ($L_m\times F$) with $L_m\leq L$. Let $\lambda^{(k)} = \{\lambda_0, \lambda_1, \ldots, \lambda_{L-1}\}$ be the set of L wavelengths used by the k[th] matrix of C. The C^k matrix partition provides matrices C_m^k such as: $C^k = \sum_m C_m^k$.

The C_m^k matrix weight is $L_m\leq L$ and, the sets of wavelengths $\lambda_m^{(k)}$ verify: $\bigcup_m \lambda_m^{(k)} = \lambda^{(k)}$.

For example in figure 3, we illustrate a matrix partitioning with m=2, L=9, L_1=6 and L_2=3.

For any matrix C_m^k, the auto-correlation value h_a is equal to one, and the cross-correlation value h_c between any two matrices is either equal to zero (no wavelength in common) or to one (wavelengths in common).

In order to obtain codes leading to different BERs i.e. various QoS, we study the different partition possibilities of a MWOOC: the objective is to select the one reaching the targeted BERs.

3.2.2 *Weight subdivision*

For a given set of N matrices $\{C^k\}$ with dimension ($L\times F$) and a desired number of services S, the partitioning method leads to a new set of matrices with dimensions respectively equal to ($L_1 \times F$), ($L_2 \times F$), …, ($L_S \times F$) and a number of users respectively equal to N_1, N_2, …, N_S. We consider that the high quality of service is provided by the initial matrices of dimension ($L \times F$). Thus, we do not split all the N matrices of C and we assume that $L_1=L$. To present the method, we consider the example of three QoS differentiation, but the method works for any number of services S.

For S=3, the values of L_2 and L_3 must verify the following condition:

$$L_1 = \alpha \times L_2 + \beta \times L_3 \qquad \text{with } (\alpha,\beta) \in \mathbb{N}^2 \qquad (3)$$

Table I reports the partition obtained with (3) for the case $\alpha=1$, $L=L_1=9$ and $L_2 \geq L_3$. We do not consider the case where L_2 and L_3 can be equal to 1 and 2 because the associated BERs are not performing enough to be investigated.

Table I: Partitionning possibilities when $L=L_1=9$

L_2	L-L_2	L_3	$\beta = \frac{L-L_2}{L_3}$	(3)
3	6	3	2	9=3+2×3
5	4	4	1	9=5+1×4
6	3	3	1	9=6+1×3

We obtain three subdivisions (L_2,L_3): (3,3), (6,3) and (5,4). Thus, with matrices from the initial code of dimension ($L \times F$), we get 4 partitioning solutions presented in figure 4. In the case (a), matrices are not divided, whereas for example in the case (d) matrices are divided into two lower weight matrices using respectively 4 and 5 wavelengths. To provide S=3 QoS, we must combine the (a), (b), (c) and (d) solutions. If we consider (a)+(c) or (a)+(d), we obtain the required number of services with a number of families K=3. We can also see that the (b) partition weight values are included in (c) (W=3), thus it can be associated with (a)+(c) to provide S=3. In this case, we get a number of families K equal to 6. Whereas if we combine partition (b) with (a) (respectively with (a)+(d)) there are two different weights (resp. four), this lead to a number of services S=2 (resp. S=4). The three possible solutions are presented in figure 5.

To determine the number of users for each code of different weights, we have to consider the number of matrices of C we allocate to each subdivision.

In the cases A and B, let P_1 be the number of matrices we do not split and P_2 be the number of matrices that we divide into two lower weight matrices. We have a total number of users equal to $P_1+2\times P_2$, with the condition $P_1+P_2 \leq N$. In the case C we have to take into account one more partition P_3. This leads to a total number of users equal to $P_1+2\times P_2+3\times P_3$ with $P_1+P_2+P_3 \leq N$. Thus, the partitioning method permits generating multi-weight 2D codes and increases the overall number of users who can communicate simultaneously.

4. ERROR PROBABILITY EXPRESSION

We consider a chip synchronous case, which corresponds to the worst case [3], and a system with K families of 2D code, with constant length F and different weights L_i: #1 family ($L_1 \times F$,L_1) with N_1 users, #2 family ($L_2 \times F$,L_2) with N_2 users …#K family ($L_K \times F$,L_K) with N_K users, and with $L_1=L \geq L_2 \ldots \geq L_K$. We aim at detecting a user from the j[th] family ($L_j \times F$,L_j) with a conventional receiver (CCR).

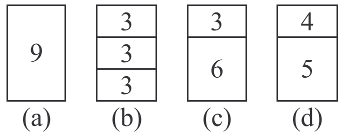

Figure 4: Division possibilities for L=9 wavelengths

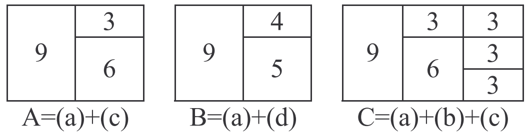

Figure 5: Different partitioning configuration to provide S=3 QoS from a MWOOC(9×F,9).

With this receiver in the noiseless case, errors appear only when the sent data is a '0' with a threshold level value $T_j = W_j = L_j$ [3].

In this case, the decision variable Z_j of a desired user #j is: $Z_j = \sum_i I_i^{(j)}$ where $I_i^{(j)}$ is the multiple access interference term due to users from #i family on the desired user from #j family.

Each code matrix has one chip set to '1' per wavelength, thus the probability for two matrices with a pulse set to '1' on a same wavelength to be on the same time slot is $1/F$. Therefore, the probability for a user from a #i family to have a chip overlap with the desired user #j is: $q_{i,j} = N_\lambda(i,j)/F$ with $N_\lambda(i,j)$ the number of mutual wavelengths used between the families #i and #j. This value is obtained from the division process. In the example provided above, considering the A subdivision and K=3: $N_\lambda(1,2)=6$, $N_\lambda(1,3)=3$ and $N_\lambda(2,3)=0$.

To calculate the interference probability P_i^j, we define the number of potential interfering users $N_{i,j}$:

$$N_{i,j} = \begin{cases} N_i - 1 & \text{if } i=j \\ N_i & \text{otherwise} \end{cases}$$

Thus, we obtain:

$$P_i^j = P_i\left(I_i^{(j)} = n_i\right) = \binom{N_{i,j}}{n_i} \left(q_{i,j}\right)^{n_i} \left(1-q_{i,j}\right)^{N_{i,j}-n_i}$$

An error occurs when the decisional variable Z_j is greater than it should be: $\sum I_i^{(j)} \geq T_j = L_j$. Finally, we obtain the error probability by considering the interference amount due to users from each family such as:

$$Pe(j) = \frac{1}{2} \sum_{n_1}^{N_{1,j}} \sum_{n_2}^{N_{2,j}} \cdots \sum_{n_K}^{N_{K,j}} P_1^j \times P_2^j \times \cdots \times P_K^j \times P\left(\sum_i n_i \geq T_j\right)$$

$$Pe(j) = \frac{1}{2} \sum_{n_1=0}^{N_{1,j}} \sum_{n_2=0}^{N_{2,j}} \cdots \sum_{n_K=0}^{N_{K,j}} \binom{N_{1,j}}{n_1} \left(\frac{q_{1,j}}{2}\right)^{n_1} \left(1-\frac{q_{1,j}}{2}\right)^{N_{1,j}-n_1}$$
$$\times \binom{N_{2,j}}{n_2} \left(\frac{q_{2,j}}{2}\right)^{n_2} \left(1-\frac{q_{2,j}}{2}\right)^{N_{2,j}-n_2} \times \ldots \times \qquad (4)$$
$$\binom{N_{K,j}}{n_K} \left(\frac{q_{K,j}}{2}\right)^{n_K} \left(1-\frac{q_{K,j}}{2}\right)^{N_{K,j}-n_K} \times P\left(\sum_i n_i \geq T_j\right)$$

We can remark that there is a lower bound of the error probability for a user from #j family which is given by the single service error probability case, considering that all N matrices of C are associated to the subdivision which contains the #j family. Thus, the error probability lower bound expression is obtained as in [8]:

$$Pe(j) = \frac{1}{2} \sum_{n_j = T_j}^{N-1} \binom{N-1}{n_j} \left(\frac{L_j}{2 \times F} \right)^{n_j} \left(1 - \frac{L_j}{2 \times F} \right)^{N - n_j - 1} \quad (5)$$

The upper bound of the error probability for a user from a #j family can be obtained from equation (4), considering the case where the #j family has only one user (the desired one) and where the N-1 available matrices of C are dedicated to the subdivision generating the most interference.

For example in the case C, suppose that the family #1 has one user, the subdivision generating the most interference is the one containing the highest number of families, i.e. L_2=L_3=3. Thus, the upper bound is reached when there are 3×(N-1) interfering users.

To validate the theoretical error probability expression (4), we consider the transmission of the three codes obtained from a MWOOC (9×73, 9, 1, 1) with the partition A. Numerical results are obtained from simulation (C language) of an OCDMA system with a CCR structure. The number of users are respectively: N_1=P_1 codes MWOOC(9×73,9), N_2=P_2 codes MWOOC(6×73,6) and N_3=P_2 codes MWOOC(3×73,3).

On figure 6, we have reported the simulated and theoretical BER values for the code MWOOC(9×73,9) as a function of N_1 with N_2=N_3=32-N_1.

We can notice that the more the number of users N_1 of the #1 family, the better the performance; this is due to the fact that as N_1 increases there are less interferer users from the #2 and #3 families. Moreover, the theoretical expressions fit with the numerical results, so we validate the theoretical formula (4). Thus, from now on, we will use (4).

5. MULTI-SERVICE APPLICATION

To evaluate the ability of this method to provide multimedia applications, let us take the example of three services, we have searched the code parameters and the required subdivisions to have three BERs respectively equal to 10^{-9}, 10^{-6} and 10^{-3}.

First, we have to search the minimal temporal code length F of a 2D code (L×F,W=L) required to have a single service BER lower than 10^{-9} for 32 active users when a CCR is used (5). This minimal value is obtained in the case L=W=12, and corresponds to a MWOOC(12×163,12).

One 1D OOC(163,12,1,1) position vector is given by: (1,2,4,8,17,42,68,73,90,110,118,153). From this vector we construct 2D matrices MWOOC(12×163,12) according (1).

Table II presents the partition possibilities of the code according (3). For each (L_1, L_2, L_3) values, the theoretical error probability bounds are calculated. This permits choosing the partition corresponding to the targeted BERs. Selected partitions are reported on Table III. For such division, we have a total number of matrices equal to P_1+2×P_2+3×P_3. N_1=P_1 matrices have a high QoS at their disposal, N_2=P_2 have a medium QoS and N_3=P_2+3×P_3 have to a low QoS.

We have plotted on figure 7 the BER of high QoS users from the Multi-Weight MWOOC(12×163,12) as a function

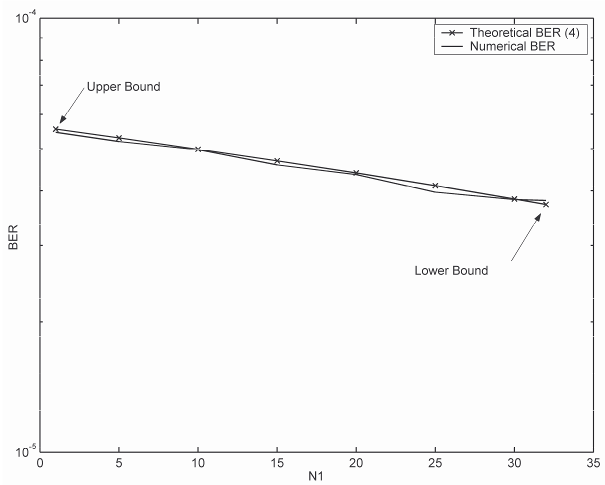

Figure 6: Theoretical and simulated BER for a Multi-Weight MWOOC(9x73,9,1,1) code with a CCR receiver.

Table II: Partitionning possibilities when L=L_1=12

L_2	L- L_2	L_3	$\beta = \frac{L - L_2}{L_3}$	(3)
3	9	3	3	12=3+3×3
4	8	4	2	12=4+2×4
6	6	3	2	12=6+2×3
		6	1	12=6+1×6
7	5	5	1	12=7+1×5
8	4	4	1	12=8+1×4
9	3	3	1	12=9+1×3

Table III: Considered partition to have BERs ≤10^{-9}, 10^{-6} and 10^{-3} and their bound probability.

12	4	4
	8	4
		4
P_1	P_2	P_3

Code	BER_{min}	BER_{max}
(12×163,12)	$2{,}27.10^{-10}$	$9{,}67.10^{-10}$
(8×163,8)	$3{,}13.10^{-7}$	$4{,}81.10^{-7}$
(4×163,4)	$2{,}74.10^{-4}$	$2{,}74.10^{-4}$

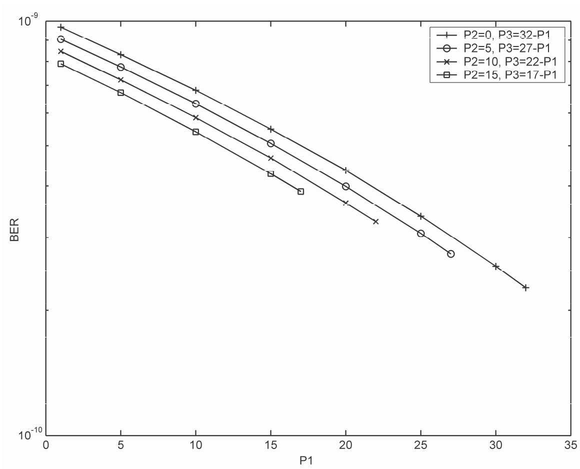

Figure 7: Performance analysis of high QoS users from a Multi-Weight MWOOC(12×163,12) with a CCR

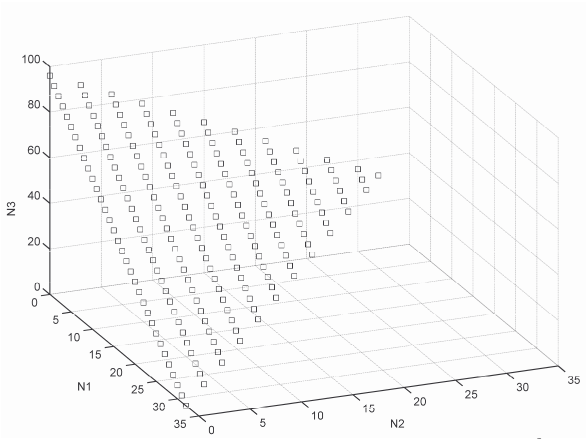

Figure 8: Number of users communicating at BERs of 10^{-9} (N_1), 10^{-6} (N_2) and 10^{-3} (N_3) with a Multi-Weight MWOOC(12×163,12) using a CCR.

of the $N_1=P_1$ values, for different values of $N_2=P_2$ (so the $N_3=P_2+3\times P_3$ value is fixed since $P_1+P_2+P_3=32$).

We can see that the error probability decreases when N_1 increases, this is due to the fact that there are less interferers from others code families. We can also remark that for a given value of N_1, the error probability gets better when N_2 increases. This is because the N_3 value decreases and so there are less interferer onto the desired user. Thus, the high QoS service is assured whatever the number of users, providing that $N_1 \leq N=32$.

On figure 8, we have plotted the number of users having respectively high, medium and low QoS using the Multi-Weight MWOOC(12×163,12) and a CCR. We can note the points (N_1, N_2, N_3): (32,0,0), (0,32,32) and (0,0,96) which correspond to the maximal values we can assign to each partition P_1, P_2 and P_3. We can see that the low QoS number of users can be up to $N_3=96$. This N_3 value decreases faster when N_1 increases than with N_2. This is due to the fact that the matrix partition to have medium QoS users also provides low QoS users.

Besides for example, if we aim at having $N_1=15$ users with high QoS and $N_2=10$ users with medium QoS, then it can be seen that we can provide $N_3=10+3\times(32\text{-}10\text{-}15)=31$ users with low QoS (i.e.$P_3=7$). Thus, in this multi-service example the number of users in the network is equal to 56 which is a significantly increase compared to the 32 users of a single service.

6. CONCLUSION

A construction method to obtain Multi-Weight MWOOC code for multimedia applications has been presented. The 2D code construction permits generating code matrices with different weights and constant length to provide Quality of Services differentiation. The theoretical error probability expression is developed when a conventional correlation receiver is used in a 2D Multi-Weight OCDMA network. We have presented a multi-service application and shown that, from a 2D code designed to provide a single service to 32 users with a BER of 10^{-9}; it is possible to provide three services with BERs of 10^{-9}, 10^{-6} and 10^{-3}. The total number of possible users has been increased from 32 up to 96. This increase can also be used to provide a multirate OCDMA transmission by allocating several codes to a user.

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