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Effect of AWGN on BER Performance of Multiuser Detection in DS-OCDMA System using Novel Multilevel Periodic Codes

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Abstract—**In this paper, we study the performance of the multiuser detection in a direct sequence optical code division multiple access (DS-OCDMA) system using novel periodic optical encoder applied to fiber-to-the-X (FTTX) passive optical network (PONs). The performance of our system is analyzed in a synchronous network using multilevel periodic codes (ML-PC) with a conventional receiver model and the results are compared with those for different receivers. Two solutions to improve the performance are proposed: the parallel interference cancellation receiver (PIC) and the successive interference cancellation receiver (SIC). We investigate the performances in terms of signal to noise ratio (SNR) and bit error rate (BER) in the presence of multiple access interference (MAI) and an additive white Gaussian noise (AWGN).**

Keywords—direct-sequence optical code-division multiple-access (DS-OCDMA), fiber-to-the-X (FTTX), passive optical network (PONs), multilevel periodic codes (ML-PC), parallel interference cancellation (PIC), successive interference cancellation (SIC), signal to noise ratio (SNR), additive white Gaussian noise (AWGN), multiple access interference (MAI).

I. INTRODUCTION

Direct-sequence code-division multiple access (DS-CDMA) is currently the subject of much research as it is a promising multiple access capability for third and fourth generations mobile communication systems.

In Direct Sequence transmission, the user data signal is multiplied by a code sequence. Mostly, binary sequences are used. To obtain better performance than those obtained by the detection single-user, multiuser detection has been investigated for links OCDMA [1] [2]. Indeed, this type of detection, already used for the radio CDMA has proven its efficacy in reducing the impact of interference on performance [3]. The advantage of the multiuser detection over single-user detection is the knowledge of codes of undesired users that evaluates more precisely the interference present in the received signal. Consequently, the data are better detected.

In this paper, we present two multiuser detection scheme: a parallel cancellation method (called PIC) and a successive interference cancellation (called SIC) developed for radiofrequency systems, applied to the direct sequence optical CDMA system, the spreading codes considered here are achieved with a new periodic coding scheme [4], that has been previously proposed for FTTX monitoring. Our study is done when the direction of data transmission is the uplink direction, from Optical Network Unit (ONU), to Optical Line Termination (OLT). Using the DS-OCDMA technique for the upstream, would provide necessary bit rate, dispensing of synchronization for this track. The bit error rate (BER) performances were reported in the case of an optical synchronous incoherent DS-OCDMA system using multilevel periodic codes (ML-PC) when applied to the fiber-to-the-x passive optical network (FTTX-PON) architecture. In the work reported here, we focus our attention on the signal to noise ratio (SNR) and bit error rate (BER) performances of the DS-OCDMA system, whereas we studied the effect of the additive white Gaussian noise (AWGN) on the system.

This paper is organized as follows: In the second section, we present the description of the DS-OCDMA system. In the third section we introduce the two methods of multiuser detection (parallel and successive interference cancellation structure), their improvement, and the impact of the AWGN on the performance of the system. In the fourth section we evaluate the performance of the proposed system through the signal to noise ratio (SNR) and the bit error rate (BER), assuming an AWGN channel.

II. SYSTÈME MODEL

In a DS-OCDMA system, users transmit binary data equiprobable and independently in an optical fiber.

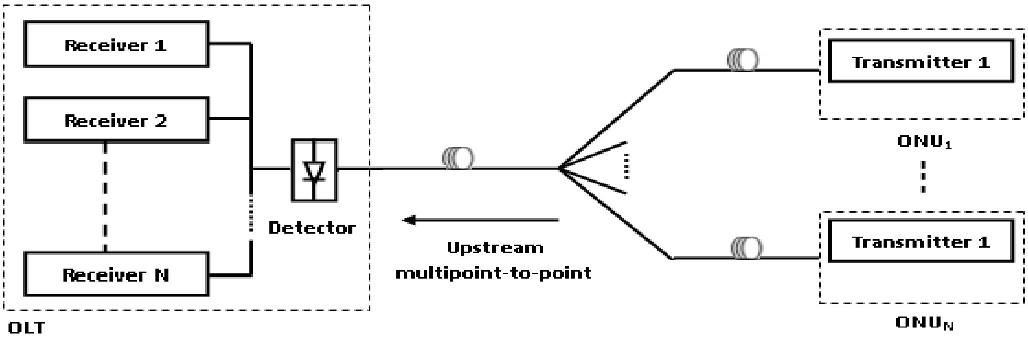

Figure 1: Direct Sequence OCDMA system

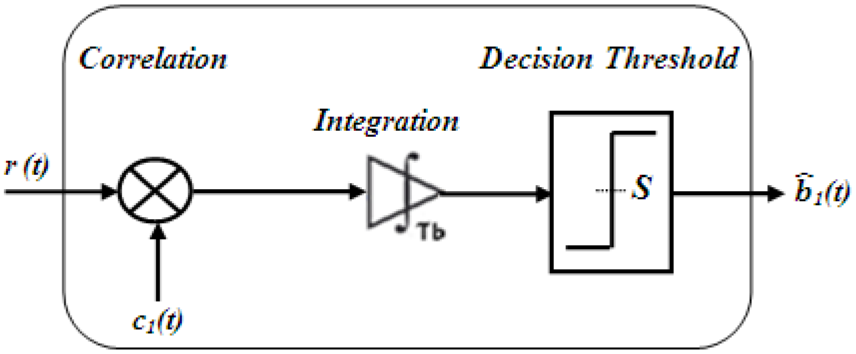

Figure 2: Conventional Correlation Receiver for User 1

Differentiation of users is done by multiplying the data by a code (Fig. 1) [5]. This code should be specific to each user, so that we can extract the data by comparing the received signal with the desired user code.

The codes studied in this paper are the multilevel periodic codes (ML-PC) [4], which are determined by the length of the silent intervals separating the multilevel pulses, i.e, its period. The codes length of the ith customers is related by the silent period between the subpulses and is given as:

$$l_{ci} = p_i w T_s c \tag{1}$$

$$p_i = l_i / cT_s \tag{2}$$

where c here is the speed of light, p_i is an integer number that determines the length of the ith encoders ring l_i, T_s is the transmitted pulse duration, and w is the weight of the code (c_i).

In DS-OCDMA system the data of active users are spread by multiplication with the code sequence, at the output of the encoder the kth user signal is obtained as:

$$e_k(t) = a_k b_k(t) c_k(t) \tag{3}$$

a_k is the power level at the output of encoder and b_k is the data transmitted by the k^{th} user. In the case of multilevel periodic codes (ML-PC), the total power for any code with weight w [4] is: $P_t = \Sigma_{j=1}^{w} \rho_j$ (4)

ρ_j is the jth subpulse power level generated by the encoder. The first subpulse power level ρ_1 is equal to $\rho_1 = s^2$. For j=2,….w the level of ρ_j can be derived as:

$$\rho_j = (1-s)^2 s^{j-1} + (1-s)\rho \tag{5}$$

s is the power coupling ratio which determines the amount of power coupled to the ring encoder proposed in [4]. It was shown in [4] that the interval of s between 0.5 and 0.6 gives good distribution for the power between the subpulses with cumulative power that depends on the weight w.

Finally, at the input of the receiver, the signal e(t) is the superposition of signals transmitted by the N users:

$$e(t) = \sum_{k=1}^{N} e_k(t-\tau_k) \tag{6}$$

With the conventional correlation receiver model (CCR), the received signal provides three functions (Fig. 2):

- Multiplying the received signal by the code of the desired user. This step, equivalent to the realization of a mask between the received signal and the code sequence, can retain only the power present in the chip unit code,

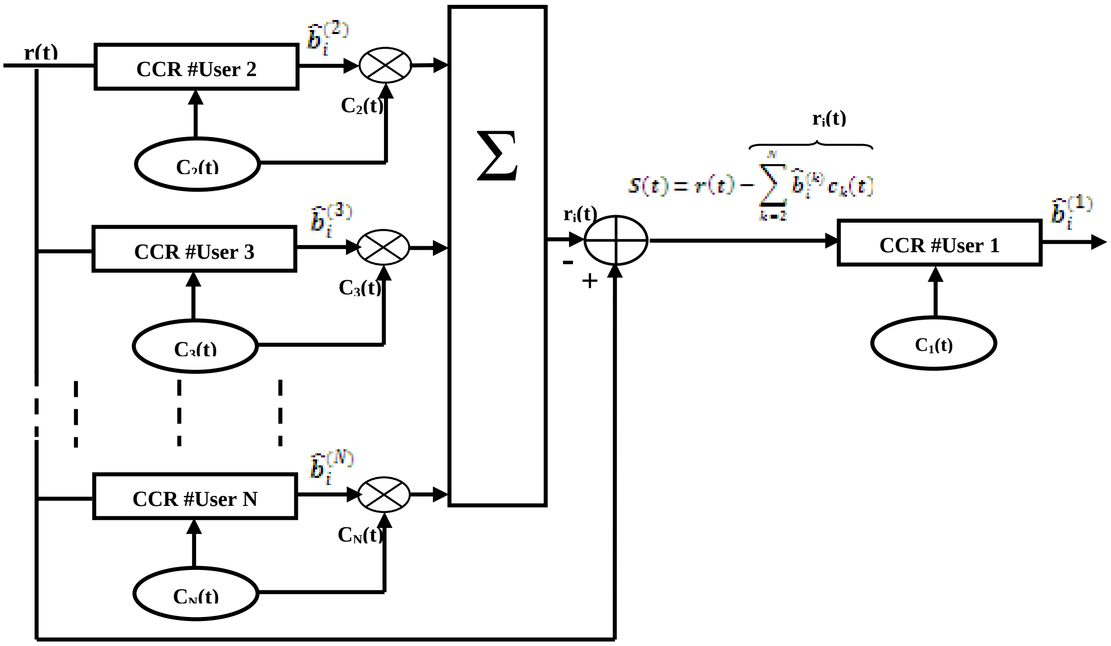

Figure 3: Schematic of the PIC receiver

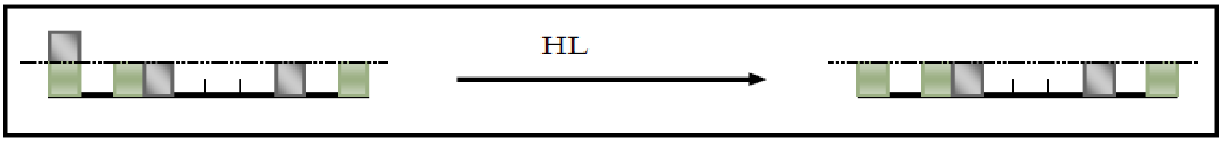

Figure 4: Effect of Hard Limiter on an example of received signal

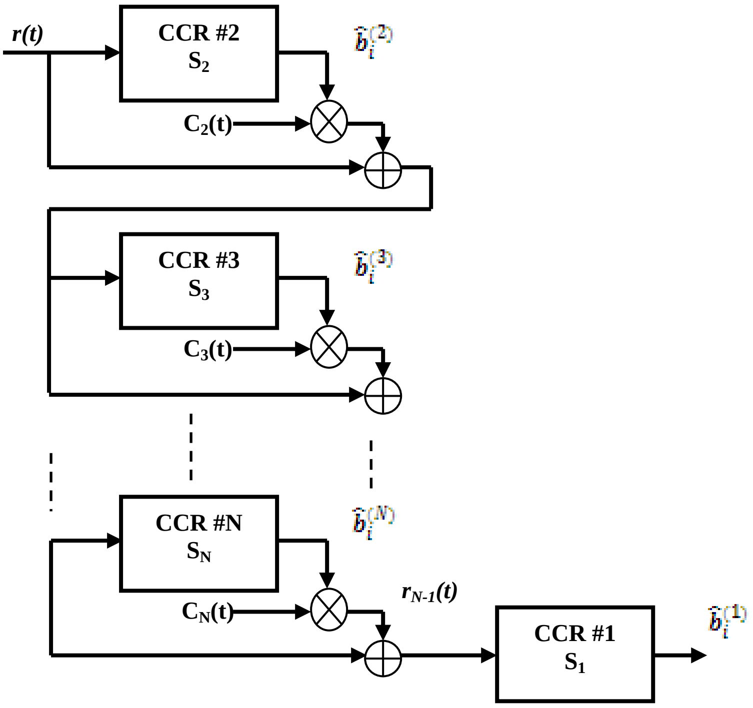

Figure 5: Schematic of the SIC receiver

- Integration of the signal obtained on the bit time: This step evaluates the total power present on the signal previously obtained during the interval of a bit time. This step provides the value of the decision variable.

- Decision making by comparison to a threshold: comparing the decision variable with the decision threshold used to obtain the estimated data.

A. Principal of parallel interference cancellation receiver

In a structure with parallel cancellation, all undesired users are detected at the same time using the conventional receiving systems (Fig. 3). The parallel interference cancellation receiver has the principle of the reproduction interference from undesired users, to remove it from the total received signal, for this the PIC requires several steps:

- The detection of data sent by each undesired user is done by the conventional correlation receiver (CCR) with a detection threshold "S_t", at the output of each receiver, we obtain the estimation $\hat{b}_i^{(k)}$ of the data sent by the undesired user # k,
- The second step is to reconstruct the signals transmitted by undesired users by multiplying the estimated data $\hat{b}_i^{(k)}$ by the corresponding code $c_k(t)$,
- We obtain in the third step, the interference term $r_i(t)$ which is actually the sum of the reconstructed signals, then it is subtracted from the received signal r(t): $S(t) = r(t) - r_i(t)$ and as, $r_i(t) = \sum_{k=2}^{N} \hat{b}_i^{(k)} c_k(t)$,
- The last step is the detection of the desired user data # 1 from the signal "cleaned" from the interference S(t). This detection is done through a CCR with a decision threshold S_f.

B. Amelioration

To improve the system performance by excluding some combinations of interference, we proposed to use the Hard Limiter device placed in front of a PIC structure.

1) Principle of hard limiter(HL)

In practice, this component removes a part of the received power to get at the end a signal which each chip contains a power equal 0 or 1. For example, in Fig. 4, we observe that the HL removed a part of the power contained in the first chip, and left unchanged the rest of the signal. Indeed, the power contained in the first chip of the received signal has a value of 2, while the one in the same chip after the action of HL is 1. Thus, the HL has eliminated a part of the interference contained in the first chip. on the other side, the chips containing a power equal to 1 before the HL remain unchanged, and those for which the power was zero. As a result, levels 0 and 1 will be unchanged, and levels greater than 1 will be reduced to one. This limitation of the power in each chip reduces the interference, and removes some interference patterns leading to an error.

2) HL+PIC

To improve the performance of the PIC, the detection of undesired users can be achieved by a HL + CCR receiver. Thanks to the limiters placed before the receivers of the undesired users, the data are therefore better estimated so the contribution of these users in the received signal is better evaluated.

C. Principle of successive interference cancellation receiver

Each stage of this receiver estimates and regenerates one estimation of the contribution of a user after the other, for subtract it from the signal. We consider, without loss of generality, that the desired user is user # 1. We assume that the system has N active users (Fig. 5). The principle of the SIC is to reproduce step by step the interference due to undesired users to remove it from the total received signal [1]. For this, the SIC requires several steps (Fig. 5):

- The first step is to detect the data sent by an undesired fixed user, to subtract from the received signal the estimated contribution of this user. To do this step, the data transmitted by the user is estimated using a CCR with a decision threshold S_2. Then the estimated signal is reconstructed by multiplication with the code of the undesired user, and subtracted from the received signal. Then we get a new signal:

$$r_1(t) = r(t) - \hat{b}_i^{(2)} c_2(t) \tag{7}$$

- This process can be repeated either on the total undesired users (in this case, the SIC has N-1 stages), or a part of the undesired users.

- At the end of the procedure, the signal $r_{N-1}(t)$ is applied to the input of the conventional receiver of the desired user # 1:

D. Impact of the AWGN on the Performance of the system

We will study the impact of noise on the performance of a DS-OCDMA system using periodic codes by analyzing our receivers studied here in absence of noise [6] and then in the presence of this imperfection.

1st case: In the synchronous case ($\tau_k = 0$) and ignoring the noise term, the only limitation for all structures (CCR, PIC or SIC), is the multiple access interference (MAI). In this case the received signal r(t) is given by the following relationship:

$$r(t) = e(t) = \sum_{k=1}^{N} a_k b_k(t) c_k(t) \tag{8}$$

r(t) is the received signal, e(t) is the transmitted signal, $b_k(t)$ is the data transmitted by user #k and $c_k(t)$ is the code related to the user #k.

Mathematically, the successive operations of the CCR receivers translate into the following expressions:

- multiplying the received signal by the code of the desired user gives r_{corr} which is the correlated signal:

$$r_{corr}(t) = \left(\sum_{k=1}^{N} a_k b_k(t) . c_k(t)\right) . c_1(t)$$
$$r_{corr}(t) = b_1(t) . c_1(t) + \sum_{k=2}^{N} a_k b_k(t) . c_k(t) . c_1(t) \tag{9}$$

- the integration of the obtained signal provides the decision variable $Z_i^{(1)}$ of the i^{th} data of user #1 is written as follows:

$$Z_i^{(1)} = \int_0^{Tb} b_i^{(1)} . c_1 dt + \sum_{k=2}^{N} b_i^{(k)} \int_0^{Tb} a_k c_k(t) . c_1(t) dt \quad (10)$$

$b_i^{(1)}$ is the i^{th} data of user #1.

- decision making by comparison with a threshold S respected the decoding rule follows:

$$\begin{cases} si \quad Z_i^{(1)} \geq S \rightarrow \hat{b}_i^{(1)} = 1 \\ si \quad Z_i^{(1)} < S \rightarrow \hat{b}_i^{(1)} = 0 \end{cases}$$

2

2^{nd} case: We consider in this case that the noises can be assimilated to an additive Gaussian noise. We considered a DS-OCDMA system in the presence of additive white Gaussian noise (AWGN) with variance σ_b^2. In this case the received signal at the input of the receiver is the sum of contributions of all users (MAI) and noise (AWGN):

$$r(t) = e(t) + b(t) = \sum_{k=1}^{N} a_k b_k(t) c_k(t) + b(t) \quad (11)$$

Considering that the desired user is the user # 1, we deduce the decision variable:

$$Z_i^{(1)} = \sum_{k=1}^{N} b_i^{(k)} \int_0^{Tb} a_k c_k(t) . c_1(t) dt + \int_0^{Tb} b(t) . c_1(t) \quad (12)$$

III. PERFORMANCE EVALUATION

A. Signal to Noise Ratio (SNR)

We consider the signal to noise ratio of the spread signal received at the input of CCR. Thus with an additive noise *n* normally distributed with zero mean and variance equal σ^2, and a total power for any code P_t (in the case of multilevel periodic codes, ML-PC), the SNR is:

$$SNR = 10 \log_{10}\left(\frac{P_t}{\sigma_b^2}\right) \quad (13)$$

We will present in this section the algorithm used in our simulation and we will analyze the results.

B. Numerical simulation

At the transmitter of the DS-OCDMA channel, we begin by the generation of periodic codes and then the random generation of bits sent by each user and random selection of N active users among users of the family, afterwards the step of the spreading is done by multiplying the data of the desired user by the corresponding code, subsequently the spreading of data of the undesired users and adding their contribution to the signal of the desired user. Finally, we sum the encoded data and transmit over an ideal channel in the beginning, and then over an AWGN channel.

At the receiver, we will follow the different stages of the different structure of multiuser detection as described above (SIC, PIC and HL+PIC). we consider both scenarios: interference only and interference plus AWGN, and we will follow the different stages of the structures described in Section II, and to analyze the performance of this structure, we will compare it with another receiver such as, the conventional correlation receiver (CCR), and the CCR improved by adding an optical limiter (known as Hard Limiter), and then the improved of PIC (HL+PIC).

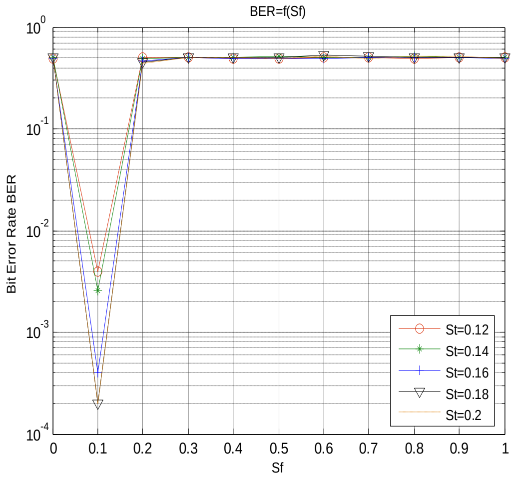

Figure 6: BER versus decision threshold of the desired users S_f using ML-PC, for PIC structure N=6

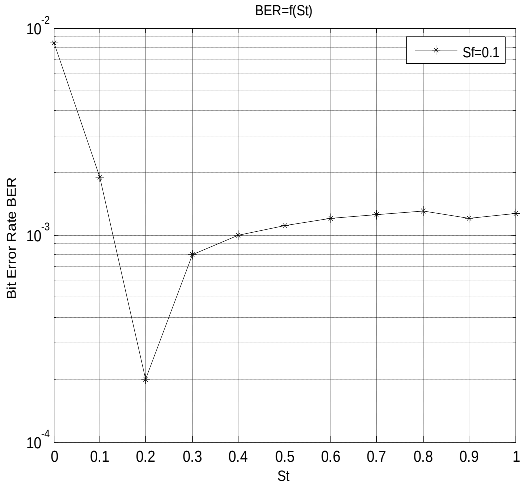

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Figure 7: BER versus decision threshold of the undesired users S_t using ML-PC, for PIC structure, N=6 Users

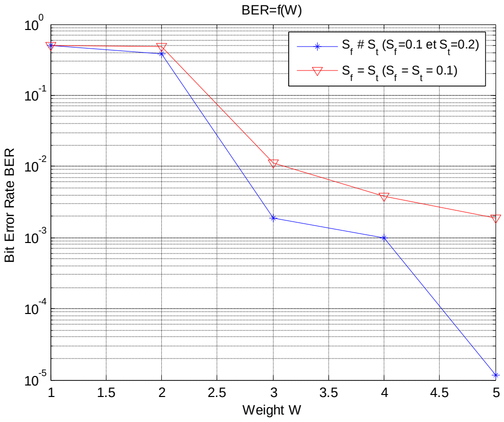

Figure 8: BER versus weight w using ML-PC, N=5 Users using SIC structure

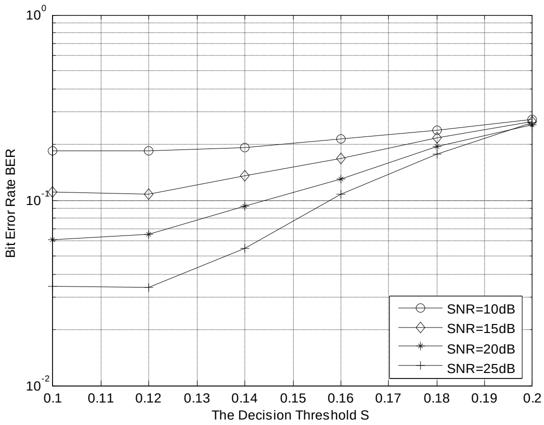

Figure 9: BER versus decision threshold for different SNR using CCR receiver, N=6 Users

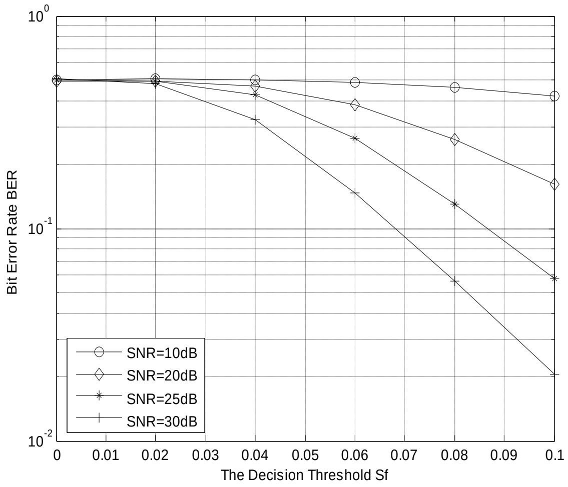

Figure 10: BER versus decision threshold for different SNR using PIC receiver, N=6 Users

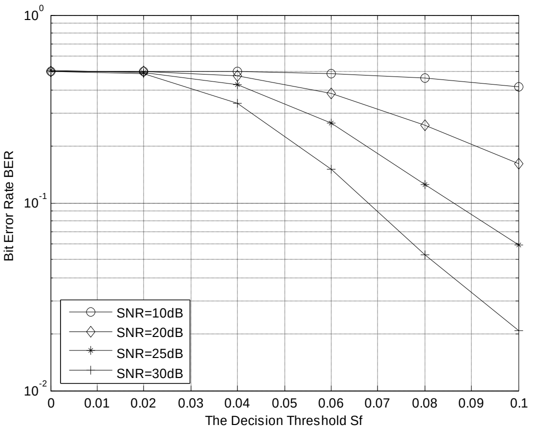

Figure 11: BER versus decision threshold for different SNR using SIC receiver, N=6 Users

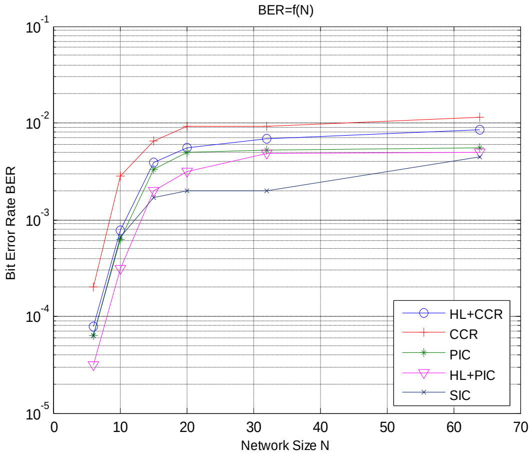

Figure 12: BER versus the network size N

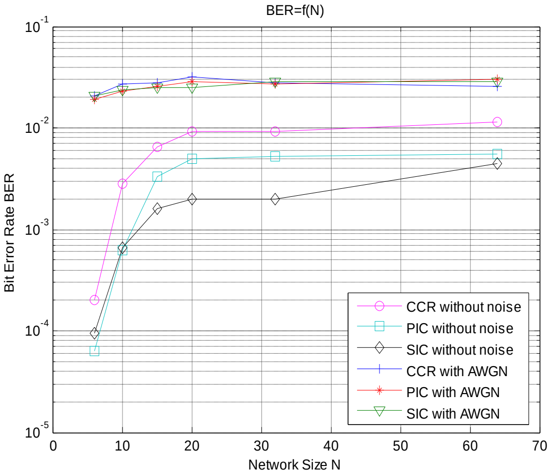

Figure 13: BER versus the network size, impact of the AWGN on the performance of the system using CCR, PIC, and SIC receivers

C. Analysis of results

The simulation has been carried out in MATLAB to evaluate the BER performance for the parallel and successive interference cancellation (PIC and SIC) and compared it with other receivers (CCR, HL+CCR, HL+PIC). So we must first determine the optimal thresholds (S_f: optimal threshold of the desired user, S_t: optimal threshold of the undesired users) of the PIC receiver.

In Fig. 6, we plotted the evolution of the BER of the PIC receivers with ML-PC codes with period p_i, weight w=5, s=0.4 and N=6 users. This performance was evaluated as a function of the S_f and varying S_t between 0.12 and 0.2. From this presentation, we can observe that the best performance is obtained for a decision threshold $S_f = 0.1$ whatever the value of S_t. Now, we will fix the value of S_f at 0.1 and we will present in Fig. 7 the variation of BER as a function of S_t with the same ML-PC code and N=6 users. So we can look that the best performance is achieved when $S_t = 0.2$.

We can conclude that the two optimal thresholds are: The optimal threshold of the undesired user: S_t=0.2, and the optimal threshold of the desired users: S_f=0.1. To optimize the detection of a SIC receiver, it is possible to assign each cancellation stage a threshold value differently.

However, the search for optimal threshold values need much calculation times for a large number of users to cancel.

To determine the optimal thresholds of our SIC receiver, we plot in Fig. 8 the variation of performance of our system in both cases, the first when $S_f = S_t$ and the other case when $S_t \neq S_f$, and to trace the variation we need to varied one of the parameters of the system, so we selected the weight w of the code, fixing the number of users N at 5 and the power coupling ratio “s” at 0.4. We can see that the best performance is obtained when St ≠ Sf.

Consequently, the results presented in the following correspond to partial optimization of the thresholds performed on two threshold values:

- thresholds cancellation stages: $S_2=S_3=\ldots=S_{N-1}=S_t=0.2$
- the threshold of the desired user: S_f=0.1

We plotted in Fig. 9 the evolution of the BER of the CCR receiver in the presence of noise as a function of the decision threshold when we used the ML-PC codes with period p_i, weight *w*=5,and s=0.5 with network size N = 6 users, for different SNR. In this figure, the best performance was obtained when SNR = 25 dB, we can see also that the optimal threshold S_{opt} for the CCR receiver is the same whatever the value of SNR, we can define the optimal threshold as follows [5]:

$$S_{opt} = P_t * w = w * \sum_{j=1}^{w} (1-s)^2 s^{j-1} + (1-s)\rho_{j-1} \qquad (14)$$

As shown in Fig. 9, and according with [5], the optimal threshold for the CCR receiver is: $S_{opt} = 0.12$.

In Fig.10 and Fig.11, we plotted the evolution of the BER performance for different values of SNR in both structure (PIC and SIC). First, we can see that the evolution is almost the same in Fig.10 and Fig.11, second, it can be seen that this figures confirmed the results obtained previously, ie the optimal threshold of the desired user S_f (in both structures) is always equal to 0,1. Finally, from this figures, we can also conclude that the best performance was achieved when the SNR = 30 dB.

In Fig. 12, we worked with the parameters estimated in the previous figures, which are:

- For CCR receiver: Sopt = 0.12 and SNR = 25 dB,
- For PIC structure: St = 0.2, Sf = 0.1 and SNR = 30 dB,
- For SIC structure: St = 0.2, Sf = 0.1 and SNR = 30 dB.

We plotted in Fig. 12, the variation of the BER as a function of the network size N, with the same ML-PC code. First, we can see that the performance of the five receivers degrade when the number of users increases, but does not exceed $2*10^{-2}$ and that thanks to the use of periodic codes.

Furthermore, we observe that for a given code, the PIC allows a number of active users more important than the CCR or HL+ CCR. Indeed, for a ML-PC code (with period p_i, w = 5 and s = 0.4) and BER = $5.5*10^{-2}$, the PIC allows 64 simultaneous users to communicate, while the CCR and HL+CCR allow only 20 users at most, to be active on the network.

Comparing the three multiuser detection structures (SIC, PIC, HL+PIC) we can observe that for a number of user less than 15 users the best performance is obtained when using the HL + PIC receiver, and the performances are very similar when using the PIC and the SIC, but when N is higher than 15 users, we can see that the SIC allows by successive interference cancellations to obtain better performance than the HL+PIC.

In Fig.13, we plotted the variation of the BER as a function of the network size to identify the impact of the additive white Gaussian noise on the performance of the DS-OCDMA system using ML-PC code in the case of the multiuser detection. So we can observe that the impact of AWGN on the performance of system is more clearly in this figure, ie. that the performance degrades when integrating the AWGN and especially in the case of CCR receiver.

It should be noted that although we worked with encoders with low cost manufacturing, installation and operation, we can maintain good performance and a number of users. Then with this type of codes (ML periodic code) we can achieve a BER = $3.125*10^{-5}$.

IV. CONCLUSION

In this paper, we investigate the multi-users detection with the parallel interference cancellation (PIC) structure by comparing it, first with the successive interference cancellation (SIC), and then with their amelioration constituted by a limiter optical device placed in front of a PIC structure (HL+PIC) and other receivers (CCR and HL+CCR), using a novel coding scheme so called multilevel periodic coding for the direct sequence optical code division multiple access system. In our system, we can achieve almost a BER = $3.125*10^{-5}$ for N = 6 users. We studied the characteristics of these codes and investigated their performance in bit error rate and additive white Gaussian noise. We derived the values for different values of optimum threshold that minimizes the bit error rate performance.

Between the two cancellation schemes, PIC is one of nonlinear multiuser detection approaches, and it can obtain obvious performance improvement at the cost of low computing complexity and short processing delay. Because of the dependence of a floor to previous stages, the exact theoretical analysis in SIC system, is very difficult to carry out. On the other hand, this structure is very effective especially for systems in which there is a near-far effect, which is not the case of the systems studied.

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