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Direct Sequence-Optical Code-Division Multiple Access (DS-OCDMA): Receiver Structures for Performance Improvement

Younes Zouine and Zhour Madini

Abstract

We present in this chapter, the performance study of a direct sequence-optical code-division multiple access (O-CDMA) link. In such systems, the main limitation is the multiple access interference (MAI). We investigate various schemes of receiver in the aim of improving the performances and mitigating MAI. Furthermore, we show the benefits of different techniques in regard to conventional ones. However, this system uses ultrashort light pulses that are sensible to the optical link parameters, especially the fiber chromatic dispersion. We have shown that when compensation dispersion devices are not deployed in the system, there is a trade-off between the limited dispersion effects and the MAI.

Keywords: PON, DS-OCDMA, multiple access interference, MAI, OOC, hard limiter, conventional correlation receiver, successive interference cancellation receiver (SIC), parallel interference cancellation receiver (PIC)

1. Introduction

The optical fiber offers a small footprint, a low attenuation, and especially a large bandwidth (estimated of the order of THz). However, the cost of a total redeployment of the optical fiber access network would be very important. In order to reduce these costs, it is possible to share the resource among several users, using a passive optical network (PON) type structure. In this case, it is necessary to set up multiple access techniques to differentiate the information associated with each user.

The two most widely used multiple access techniques for optical communications are time-division multiple access (TDMA) and wavelength-division multiple access (WDMA). These two techniques can constitute an economic brake, because the first requires the synchronization of all terminal equipment and the second one requires tunable wavelength filters to adapt to the desired wavelength. Another technique derived from radiofrequency systems has been envisaged for several decades for optical communications: code-division multiple access (CDMA) [1, 2].

In an OCDMA system, the manipulation of the signals can be considered either coherently or incoherently. In a coherent approach, the characteristics of the optical

signal measured are amplitude and phase. This configuration requires having a local oscillator synchronized to the optical frequency on reception, which increases the cost of implementation. Since the light wave can be positive or negative, data spreading can be carried out using bipolar codes such as radiofrequency.

But most studies on optical CDMA are about inconsistent systems, much simpler and, therefore, less expensive. They are usually based on a modulation scheme called “intensity modulation-direct detection” (IM-DD), and it is the luminous intensity, positive quantity, which is the measured characteristic of the optical signal. Bipolar codes can no longer be used. Unipolar quasi-orthogonal codes are used.

This chapter is organized as follows: in Sections 1 and 2, a brief description on the state-of-the-art of the DS-OCDMA technique and its advantages over TDMA and WDMA are presented. In Section 3, a study of a DS-OCDMA system using a CCR and CCR with HL is reported. Section 4 is devoted to multiuser receivers such as SIC and PIC receivers. Section 5 is dedicated to the impact of chromatic dispersion on DS-OCDMA performances. Finally, conclusions are drawn in Section 6.

2. The optical CDMA network

Every user utilizes an amplitude shift keying (ASK) especially the on/off keying modulation to transmit all the binary data via a common optical fiber. The encoder impresses a sequence code upon the binary data (**Figure 1**). The sequence code is specific to each user, in order to be able to extract the data by correlation at the end receiver. For the data recovery, the received signal would be compared at first to the sequence code, and then to a threshold level at the comparator.

For low multiple access interference (MAI) and error probability, the chosen codes must have good correlation properties. In this chapter, we consider optical orthogonal codes (OOC) [1]. A class of codes is defined by $(F, W, \lambda_a, \lambda_c)$ where F is the length of the sequences, W is the weight, and λ_a and λ_c the auto- and crosscorrelation constraints, respectively. The maximum number of users N in the OOC's class is defined as: $N(F, W, 1, 1) = \left\lfloor \frac{F-1}{W(W-1)} \right\rfloor$.

The code signature, $c_k(t)$, of the k^{th} user is $c_k(t) = \sum_{j=-\infty}^{\infty} c_j^{(k)} P_{T_c}(t - jT_c)$ where $P_{T_c}(t)$ is a unit rectangular pulse with duration of one chip T_c and $\{c_j^{(k)}\} \in \{0, 1\}$ is the j^{th} value of the k^{th} user spreading code. In general, in the case of $\lambda_a = \lambda_c = \lambda$, the number of users N is limited by the Johnson bound [1], given by the relation:

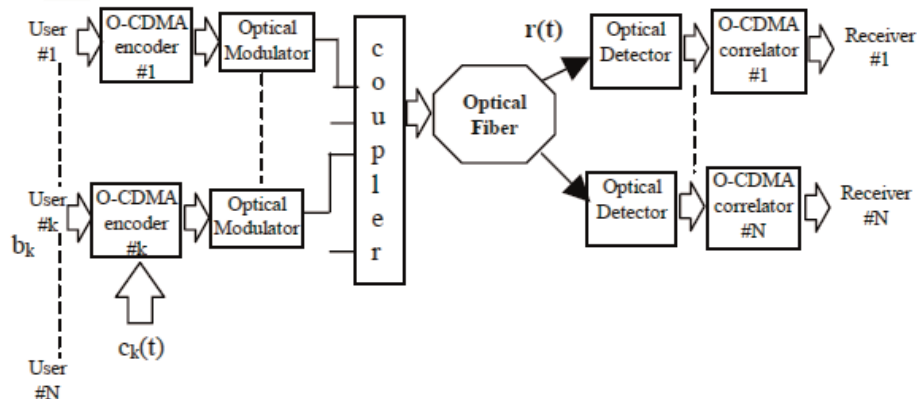


Figure 1.
Synoptic scheme of a DS-OCDMA system.

$$N(F, W, \lambda_a, \lambda_c) \leq \left\lfloor \frac{1}{W} \left\lfloor \frac{F-1}{W-1} \left\lfloor \frac{F-2}{W-2} \left[\dots \left[\frac{F-\lambda}{W-\lambda} \right] \dots \right] \right\rfloor \right\rfloor \right\rfloor. \quad (1)$$

The N output signals are directed via optical devices, such as star couplers, toward all receivers along the optical fiber. The received signal, $r(t)$, is the sum of signals transmitted by all active users:

$r(t) = \sum_{k=1}^N s_k(t - \tau_k)$ where s_k is the transmitted signal of k^{th} user and τ_k is the delay of user k .

The transmitted signal s_k is given by the following equation: $s_k(t) = b_k(t)c_k(t)$ where

- $b_k(t) = \sum_{i=-\infty}^{\infty} b_i^{(k)} P_{T_b}(t - iT_b)$ represents the data of the k^{th} user
- $b_i^{(k)}$ is the i^{th} data bit of k^{th} user, and $\{b_i^{(k)}\} \in \{0,1\}$
- $P_{T_b}(t)$ is a rectangular pulse of duration T_b

$$r(t) = \sum_{k=1}^N \sum_{i=-\infty}^{\infty} \sum_{j=0}^{F-1} m_{i,j}^k P_{T_c}(t - iT_b - jT_c - \tau_k) \text{ where } m_{i,j}^k = C_j^k \cdot b_i^k. \quad (2)$$

3. Single-user detection

The receiver is a critical part, because according to its structure and its adequacy to the considered codes, it will condition the performances of the system. Among the main receivers envisaged for optical CDMA, one can distinguish different types:

- Single-user receivers, for which only the knowledge of the code of the desired user is necessary. For these receivers, the interference generated by the other users is not taken into account and is considered as noise. As this interference increases significantly with the number of active users, these receivers make many errors in a busy network.
- Multiuser receivers, for which knowledge of the codes of other users is required. These receivers are more complex than single-user receivers. They use knowledge of undesired user codes to more reliably estimate the desired user. As a result, they allow better performance.

3.1 Conventional correlation receiver (CCR)

In a DS-OCDMA system using a CCR receiver, the spread spectrum is achieved by directly multiplying a signature code sequence with the data to be transmitted. It provides three steps:

- At first, in reception, the receiver multiplexes the received signal with the code of the desired user.
- In this step, the multiplier output signal is reformatted via an integrator in order to evaluate the total power per bit. The output signal presents the decision variable
- In the end, the decision variable will be compared to the value of the threshold S of the decision-making block in order to make the estimated data.

The block diagram of the desired user's conventional receiver is shown in **Figure 2**.

Assuming that the user #1 is the desired user, the decoding part of the DS-OCDMA system is performed by correlation. The received signal is multiplied by the code of the desired user:

$$r_{corr}(t) = r(t) \cdot c_1(t) = \left(\sum_{k=1}^N b_k(t) \cdot c_k(t) \right) \cdot c_1(t) \quad (3)$$

$$r_{corr}(t) = b_1(t) \cdot c_1(t) + \sum_{k=2}^N b_k(t) \cdot c_k(t) \cdot c_1(t). \quad (4)$$

At the output of the integration block, we will get the decision variable value $Z_i^{(1)}$

$$Z_i^{(1)} = \int_0^{T_b} r_{corr}(t) dt = \int_0^{T_b} \left(\sum_{k=1}^N b_k(t) \cdot c_k(t) \right) \cdot c_1(t) dt \quad (5)$$

$$\begin{aligned} Z_i^{(1)}(t) &= \underbrace{\int_0^{T_b} b_i^{(1)}(t) \cdot c_1(t) dt}_i + \underbrace{\int_0^{T_b} \left(\sum_{k=2}^N b_i^{(k)}(t) \cdot c_k(t) \right) \cdot c_1(t) dt}_{ii} \\ &= \int_0^{T_b} b_1(t) \cdot c_1(t) dt + \int_0^{T_b} I(t) \cdot c_1(t) dt \end{aligned} \quad (6)$$

where $I(t) = \sum_{k=2}^N b_i^{(k)}(t) \cdot c_k(t)$.

The second term of this expression represents the multiple access interference (MAI) term due to all the nondesired users. It depends on the number of active users N and the OOC's correlation properties.

Then, a comparison of the decision variable with the threshold level S has been done. Recording the comparison result, an estimation of the transmitted bit, $\hat{b}_1(t)$, is given. An error happened when the MAI term is greater than the threshold level S and the data $\hat{b}_1(t)$ are 0.

Analytical upper bound expression of the error probability has been demonstrated and presented by Salehi et al in [1]:

$$P_{es} \leq \frac{1}{2} \sum_{i=0}^{N-1} \binom{N-1}{i} \left(\frac{W^2}{2F} \right)^i \left(1 - \frac{W^2}{2F} \right)^{N-1-i} \quad (7)$$

Curves in **Figure 3** show that the performances are degraded as the number of users increases. If the threshold level value, S , is chosen close to W , the errors number decreases.

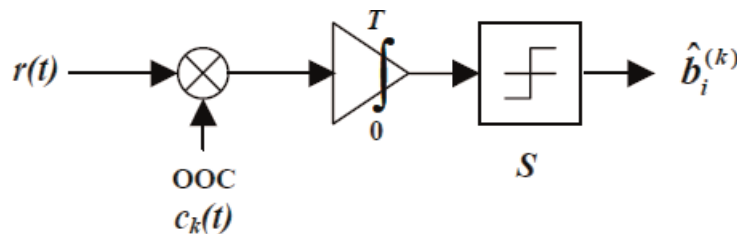


Figure 2.
The conventional correlation receiver (CCR).

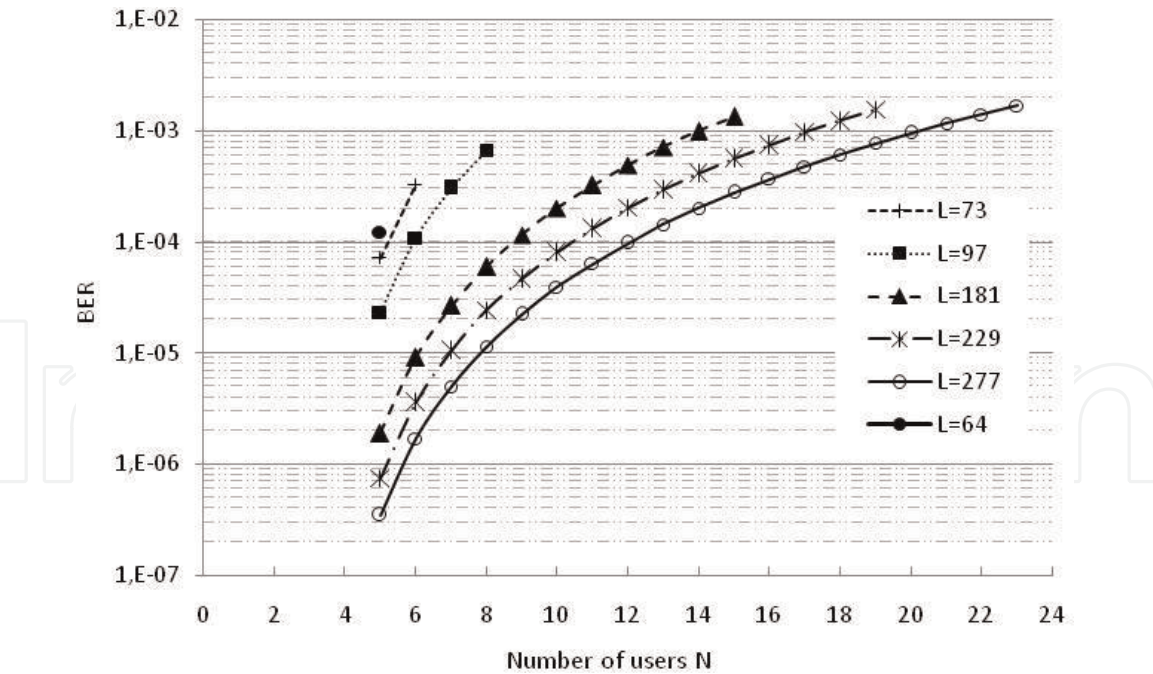


Figure 3.
BER as a function of the number of users for different lengths of the code.

3.2 Conventional correlation receiver with hard limiter (HL + CCR)

In order to limit the power of interfering users, an optical hard limiter (OHL) can be used. An ideal OHL function is defined as:

$$g(x) = \begin{cases} 0 & \text{if } x < 1 \\ 1 & \text{if } x \geq 1 \end{cases} \tag{8}$$

where 1 is the normalized optical power value of one chip.
So, if a received optical power x is bigger than or equal to 1, it will be clipped to 1. On the other hand, if a received optical power x is smaller than 1, it will be set to 0. Consequently, for $S=W$, an error can occur, if all the code chips are overlapped. Therefore, all other IAM configurations will be canceled. For the ideal chip synchronous case, the theoretical expression of the HL + CCR's error probability is given by [1, 3, 4].

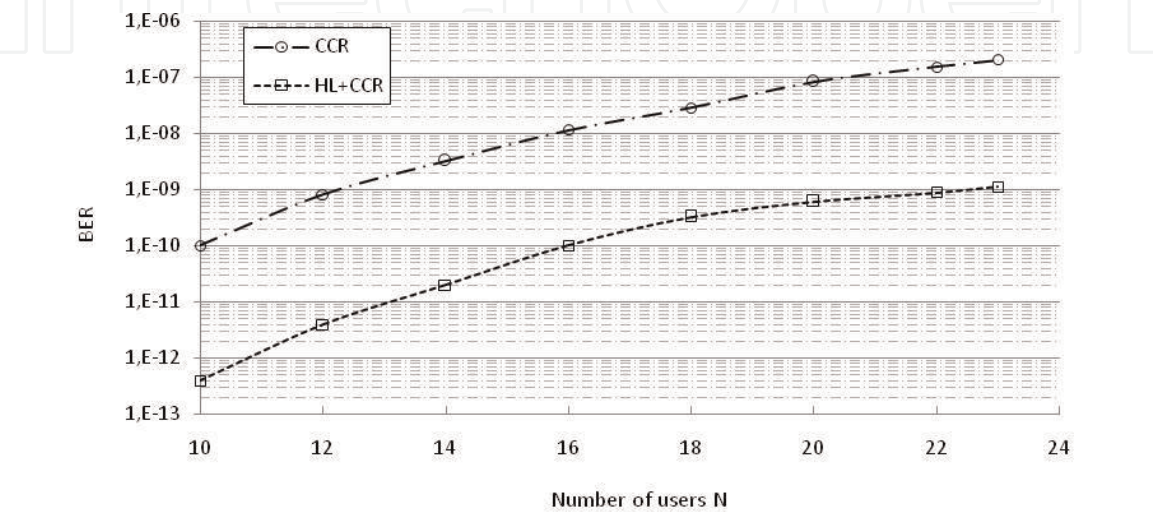


Figure 4.
Receiver's performances as a function of number of users.

$$P_{ehl} = \frac{1}{2} \binom{W}{S} \prod_{i=0}^{S-1} \left(1 - \left(1 - \frac{W^2}{2F} \right)^{N-1-i} \right) \quad (9)$$

Figure 4 shows the comparison between theoretical performances of the CCR and HL + CCR as a function of the active users number N , for $F = 1000$, $W = 7$, and $S = 7$. It is well verified that the HL + CCR provides better performance than the CCR.

4. Multiuser detection

In order to obtain better performances than those obtained by single-user detection, multiuser detection has been studied for OCDMA links [5–7]. Indeed, this type of detection, already used for wireless CDMA, has proved its effectiveness in reducing the impact of interference on performance.

The advantage of multiuser detection over single-user detection is the knowledge of undesired user codes that allows finer evaluation of the interference present in the received signal. As a result, the data are better detected.

These detectors operate in two main stages:

1. estimating all or part of the interference present in the received signal.
2. detecting the desired user data after subtracting from received signal the estimated interference.

In the CDMA systems, we can distinguish between two types of multiuser detectors:

- Successive interference cancellation receiver (SIC).
- Parallel interference cancellation receiver (PIC).

4.1 Optical successive interference cancellation

The aim of the proposed method is the estimation of interference from interfering users. Once the IAM is determined, it is deducted from the received signal before detecting the desired user. The optical successive interference cancellation structure is shown in **Figure 5**. We assume that the desired user is the user $n^\circ \# 1$.

The optical-SIC receiver has the knowledge of all the active users' codes patterns, and we assume that all the users have the same transmitting energy. So, there are no strongest interfering signals [8].

The first step provides the estimation $\hat{b}_i^{(N)}$, for example, of the data of the N^{th} undesired user by application of the traditional correlation method.

Then, the transmitting signal of the N^{th} user is reproduced and removed from the received signal $r(t)$. We call the signal received after the subtraction, $s_1(t)$, which referred to output signal of the first cancellation stage ($C_s = 1$):

$$\begin{aligned} s_1(t) &= r(t) - \hat{b}_i^{(N)} c_N(t) \\ &= \hat{b}_i^{(1)} c_1(t) + \sum_{j=2}^{N-1} \hat{b}_i^{(j)} c_j(t) + \left(b_i^{(N)} - \hat{b}_i^{(N)} \right) c_N(t) \end{aligned} \quad (10)$$

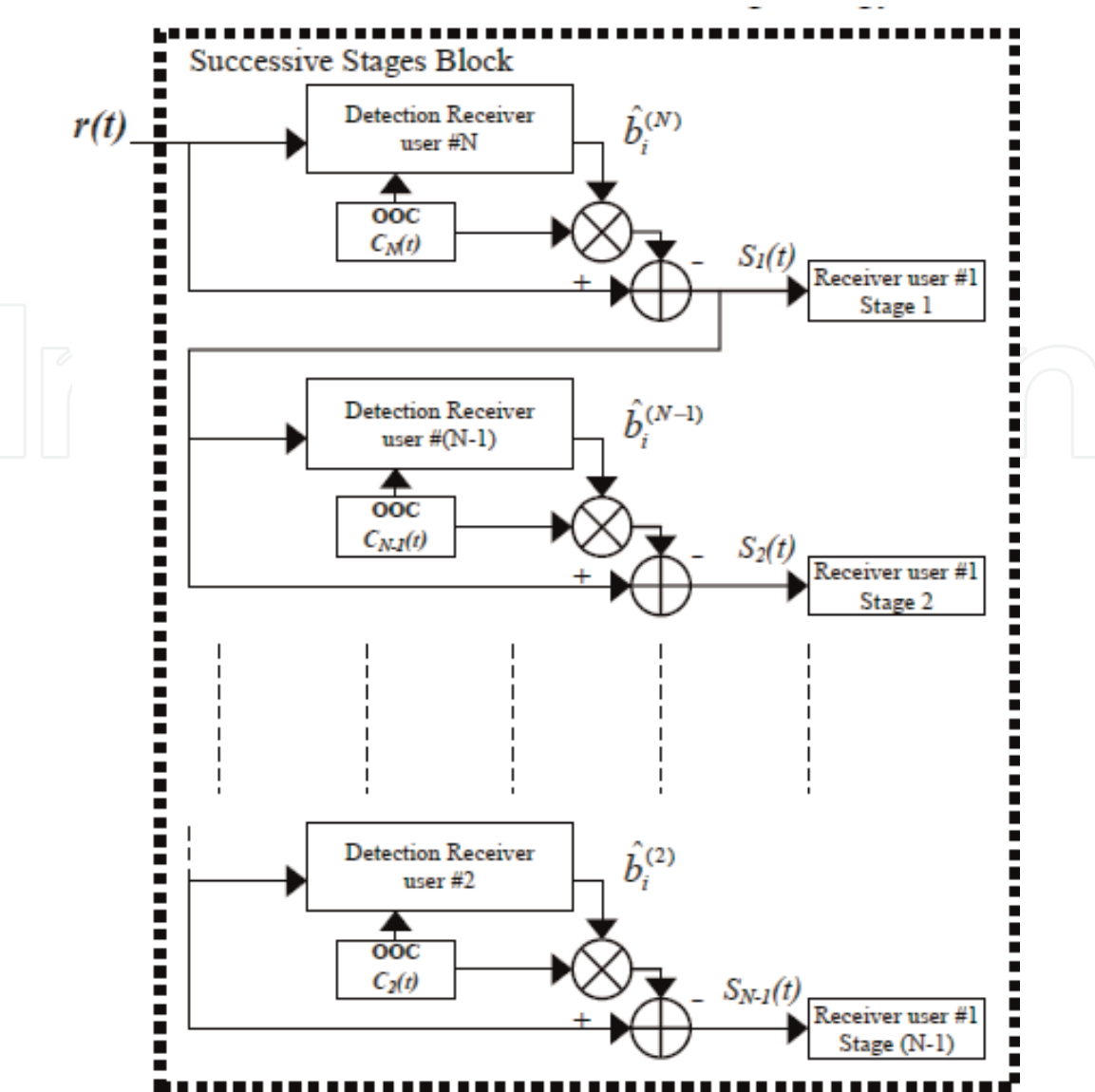


Figure 5.
Principle of the optical-SIC receiver.

The next step is the detection and estimation of the desired user data, for example, user 1, by conventional correlation method. The suppression of the undesired users could take until $N-1$ stages. At the output of the successive stages block, we obtain such signal before the conventional receiver for the user 1:

$$\begin{aligned} s_{N-1}(t) &= s_{N-2}(t) - \hat{b}_i^{(N)} c_N(t) \\ &= s_{N-3}(t) - \hat{b}_i^{(N)} c_N(t) - \hat{b}_i^{(N-1)} c_{N-1}(t) \\ &\dots \\ &= r(t) - \sum_{j=2}^N \hat{b}_i^{(j)} c_j(t) \\ &= \sum_{j=1}^N b_i^{(j)} c_j(t) - \sum_{j=2}^N \hat{b}_i^{(j)} c_j(t) \\ &= b_i^{(1)} c_1(t) + \sum_{j=2}^N \left(b_i^{(j)} - \hat{b}_i^{(j)} \right) \cdot c_j(t) \end{aligned} \tag{11}$$

4.1.1 First cancelation stage

We consider that noise perturbation is less significant than interference contribution, so the performances are linked only to MAI.

The decision variable for the desired user #1 is $Z_i^{(1)} = Wb_i^{(1)} + I_1 + A_1$ where:

- $I_1 = \sum_{k=3}^N \int_0^{T_b} b_i^{(k)} c_k(t) c_1(t) dt$ is The MAI at the output of the other users
- $A_1 = \left(b_i^{(N)} - \hat{b}_i^{(N)} \right) \int_0^{T_b} c_N(t) c_1(t) dt$ term linked to the cancelation of the user #N.

The cancelation term A_1 can only take two values 0 and -1 . Indeed, as we have conventional receivers on this stage, there are only errors for the data $b_i^{(N)}$ equal to 0, so:

$$A_1 = \begin{cases} 0 & \text{si } (b_i^{(N)} = \hat{b}_i^{(N)} \text{ (if no error in detection) }) \\ -1 & \text{if error in detection} \end{cases}.$$

The error probability is

$$P_{e1} = \frac{1}{2} P_{e10} + \frac{1}{2} P_{e11}. \quad (12)$$

where $P_{e10} = \text{prob}(\hat{b}_i^{(1)} = 1/b_i^{(1)} = 0)$ and $P_{e11} = \text{prob}(\hat{b}_i^{(1)} = 0/b_i^{(1)} = 1)$

$$\begin{aligned} P_{e11} &= \text{prob}(Z_i^{(1)} < S_1/b_i^{(1)} = 1) \\ &= \text{prob}(W + I_1 + A_1 < S_1/b_i^{(1)} = 1) \end{aligned} \quad (13)$$

$$\begin{aligned} P_{e11} &= \text{prob}(A_1 = -1/b_i^{(1)} = 1) \cdot \text{prob}(I_1 < S_1 - W + 1/b_i^{(1)} = 1) \\ &\quad + \text{prob}(A_1 = 0/b_i^{(1)} = 1) \cdot \text{prob}(I_1 < S_1 - W/b_i^{(1)} = 1) \end{aligned} \quad (14)$$

$$\text{prob}(I_1 < S_1 - W + 1/b_i^{(1)} = 1) = \sum_{i=0}^{S_1-W} C_{N-2}^i \left(\frac{W^2}{2L} \right)^i \left(1 - \frac{W^2}{2L} \right)^{N-2-i}. \quad (15)$$

We define the function

$$f(a, b, k) = \sum_{i=a}^b C_k^i \left(\frac{W^2}{2L} \right)^i \left(1 - \frac{W^2}{2L} \right)^{k-i}. \quad (16)$$

$f(a, b, k) = 0$ si $a > b$

then $\text{prob}(I_1 < S_1 - W + 1/b_i^{(1)} = 1) = f(0, S_1 - W, N - 2)$.

Similarly, on the one hand, we have

$$\text{prob}(I_1 < S_1 - W/b_i^{(1)} = 1) = f(0, S_1 - W - 1, N - 2).$$

On the other hand, we have

$$\begin{aligned}
 \text{prob}\left(A_1 = -1/b_i^{(1)} = 1\right) &= \text{prob}\left(b_i^{(N)} - \hat{b}_i^{(N)} = -1/b_i^{(1)} = 1\right) \cdot \text{prob}\left(\int_0^{T_b} c_N(t)c_1(t)dt = 1\right) \\
 &= \frac{W^2}{L} \cdot \frac{1}{2} \text{prob}\left(\hat{b}_i^{(N)} = 1/b_i^{(N)} = 0/b_i^{(1)} = 1\right) \\
 &= \frac{1}{2} \frac{W^2}{L} \text{prob}\left(Z_i^{(N)} \geq S_N/b_i^{(1)} = 1 \text{ et } b_i^{(N)} = 0\right) ; \\
 &= \frac{1}{2} \frac{W^2}{L} f(S_N - 1, N - 2, N - 2) \\
 \text{prob}\left(A_1 = 0/b_i^{(1)} = 1\right) &= 1 - \text{prob}\left(A_1 = -1/b_i^{(1)} = 1\right) \\
 &= 1 - \frac{1}{2} \frac{W^2}{L} f(S_N - 1, N - 2, N - 2)
 \end{aligned} \tag{17}$$

hence

$$\begin{aligned}
 P_{e11} &= \frac{1}{2} \frac{W^2}{L} f(S_N - 1, N - 2, N - 2) \cdot f(0, S_1 - W, N - 2) \\
 &+ \left(1 - \frac{1}{2} \frac{W^2}{L} f(S_N - 1, N - 2, N - 2)\right) \cdot f(0, S_1 - W - 1, N - 2) . \tag{18} \\
 &= \frac{1}{2} \frac{W^2}{L} f(S_N - 1, N - 2, N - 2) \cdot f(0, S_1 - W, N - 2)
 \end{aligned}$$

In the same way, we calculate the probability of error in the case where the desired user (n ° 1) has sent the data “0”:

$$\begin{aligned}
 P_{e10} &= \text{prob}\left(Z_i^{(1)} \geq S_1/b_i^{(1)} = 0\right) \\
 &= \text{prob}\left(I_1 + A_1 \geq S_1/b_i^{(1)} = 0\right) \\
 &= \text{prob}\left(A_1 = -1/b_i^{(1)} = 0\right) \cdot \text{prob}\left(I_1 \geq S_1 + 1/b_i^{(1)} = 0\right) \\
 &+ \text{prob}\left(A_1 = 0/b_i^{(1)} = 0\right) \cdot \text{prob}\left(I_1 \geq S_1/b_i^{(1)} = 0\right) \\
 \text{prob}\left(I_1 \geq S_1 + 1/b_i^{(1)} = 0\right) &= f(S_1 + 1, N - 2, N - 2) \\
 \text{prob}\left(I_1 \geq S_1/b_i^{(1)} = 0\right) &= f(S_1, N - 2, N - 2) ; \\
 \text{prob}\left(A_1 = -1/b_i^{(1)} = 0\right) &= \frac{1}{2} \frac{W^2}{L} f(S_N, N - 2, N - 2) \\
 \text{prob}\left(A_1 = 0/b_i^{(1)} = 0\right) &= 1 - \frac{1}{2} \frac{W^2}{L} f(S_N, N - 2, N - 2)
 \end{aligned} \tag{19}$$

hence

$$P_{e_{10}} = \frac{1}{2} \frac{W^2}{L} f(S_N, N-2, N-2) \cdot f(S_1 + 1, N-2, N-2) + \left(1 - \frac{1}{2} \frac{W^2}{L} f(S_N, N-2, N-2)\right) \cdot f(S_1, N-2, N-2) \quad (20)$$

4.1.2 Second and $(N-1)^{th}$ cancelation stage

The decision variable for the desired user #1 is:

$$Z_i^{(1)} = Wb_i^{(1)} + I_2 + A_1 + A_2$$

where $I_2 = \sum_{k=2}^{N-2} \int_0^{T_b} b_i^{(k)} c_k(t) c_1(t) dt$, $A_1 = \left(b_i^{(N)} - \hat{b}_i^{(N)}\right) \int_0^{T_b} c_N(t) c_1(t) dt$, and $A_2 = \left(b_i^{(N-1)} - \hat{b}_i^{(N-1)}\right) \int_0^{T_b} c_{N-1}(t) c_1(t) dt$.

In this case, the term A_2 can take three values (-1.0 and $+1$):

$$A_1 = \begin{cases} -1 & \text{if an error is made on the data } b_i^{(N-1)} = 0 \left(\hat{b}_i^{(N-1)} = 1\right) \\ 0 & \text{if } \left(b_i^{(N-1)} = \hat{b}_i^{(N-1)}\right) \text{ no error in detection} \\ +1 & \text{if an error is made on the data } b_i^{(N-1)} = 1 \left(\hat{b}_i^{(N-1)} = 0\right) \end{cases}, \quad (21)$$

hence, $P_{e_2} = \frac{1}{2} P_{e_{21}} + \frac{1}{2} P_{e_{20}}$,

where $P_{e_{21}} = \text{prob}\left(\hat{b}_i^{(1)} = 0 / b_i^{(1)} = 1\right)$ and $P_{e_{20}} = \text{prob}\left(\hat{b}_i^{(1)} = 1 / b_i^{(1)} = 0\right)$

$$\begin{aligned} P_{e_{21}} &= \text{prob}\left(Z_i^{(1)} < S_1 / b_i^{(1)} = 1\right) \\ &= \text{prob}\left(W + I_2 + A_1 + A_2 < S_1 / b_i^{(1)} = 1\right) \\ &= \text{prob}\left(A_1 = 0 / b_i^{(1)} = 1\right) \cdot \text{prob}\left(W + I_2 + A_2 < S_1 / b_i^{(1)} = 1\right) \\ &\quad + \text{prob}\left(A_1 = -1 / b_i^{(1)} = 1\right) \cdot \text{prob}\left(W + I_2 + A_2 < S_1 + 1 / b_i^{(1)} = 1\right) \end{aligned} \quad (22)$$

and

$$\begin{aligned} P_{e_{20}} &= \text{prob}\left(Z_i^{(1)} \geq S_1 / b_i^{(1)} = 0\right) \\ &= \text{prob}\left(I_2 + A_1 + A_2 \geq S_1 / b_i^{(1)} = 0\right) \end{aligned}$$

The calculation of the probability of error requires the determination of more and more terms. We have calculated the error probabilities by using the iterative method [8].

Figure 6 shows the theoretical and simulation bit error rate (BER) versus the threshold values of an OOC(73,4,1) for the conventional and the first cancelation stage of the Opt-SIC. We could see that the theoretical lines correlate with the simulation ones, and the Opt-SIC outperforms the traditional correlation receiver. From here on, we could validate the theoretical figures in order to show the performance of such receiver.

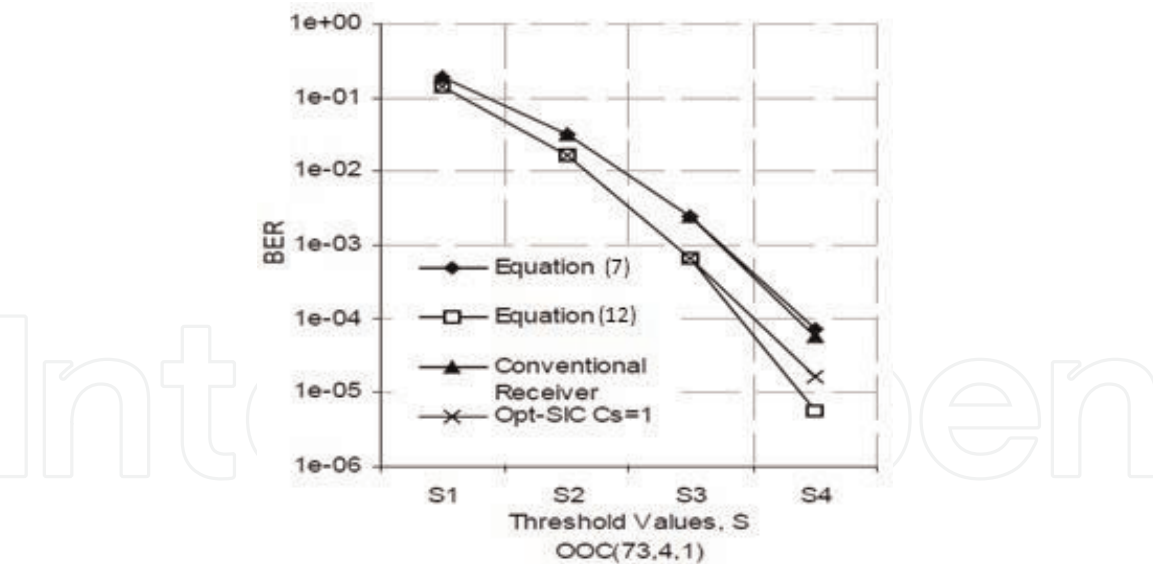


Figure 6.
Bit error rate (BER) versus the threshold values for a code length, $F = 73$ and for the conventional and the first cancellation stage.

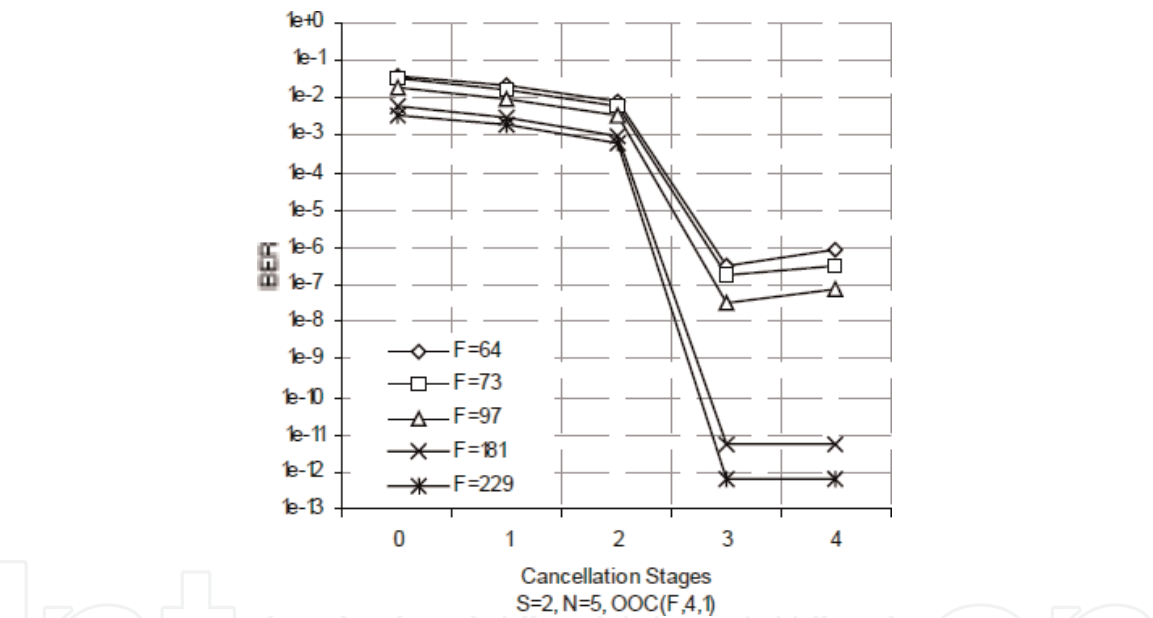


Figure 7.
The BER of the Opt-SIC system versus the cancellation stage for different code lengths and for threshold value equal to 2.

First, in order to evaluate the number of cancellation stages (C_s), we have studied the SIC performances with modifying the code weight. We can remark, in **Figure 7**, that when the number of cancellation stages increases, the BER first decreases slowly, and after a high decrease, it reaches a floor. Thus, it is not necessary to eliminate all $N-1$ stages in the SIC method to obtain a correct optical BER rate (10^{-9}). We can also just change the code length to obtain this achievement.

Moreover, in order to illustrate the benefit of the SIC in regard to conventional receivers, we have plotted on **Figure 8** the evolution of the BER as a function of the code weight W . We can observe that we obtain better performances with the SIC than with the CCR and the HL + CCR. Moreover, we can point out that the SIC is all the more performing when the BER decreases for the CCR.

In this section, an optical successive interference cancellation was examined, a technique based on the conventional O-CDMA receiver, in which the MAI is

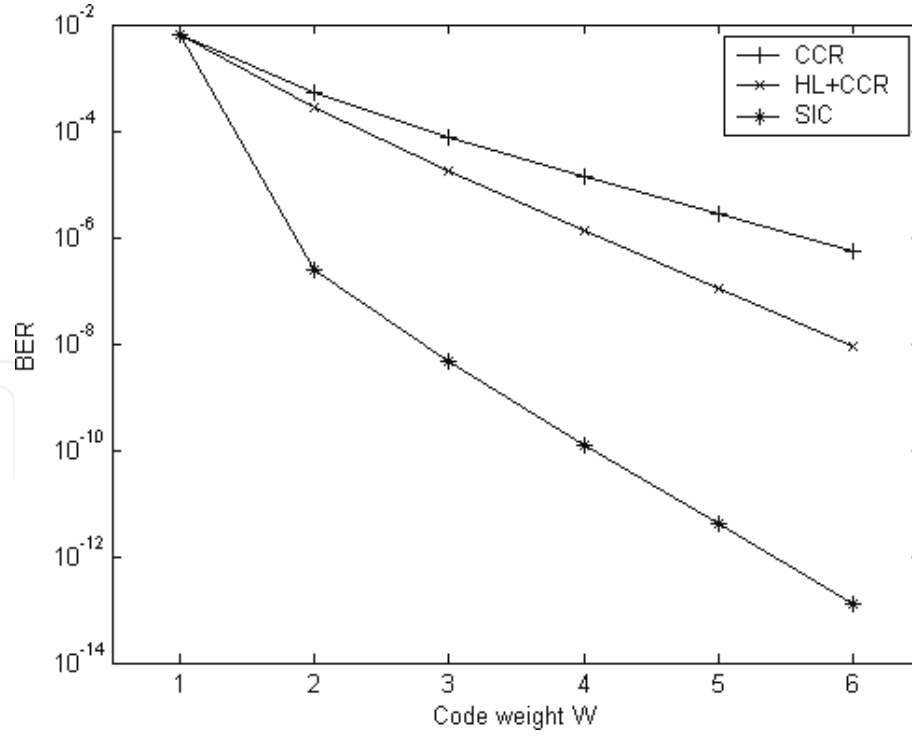


Figure 8.

BER as a function of the code weight W for $F = 361$ and $N = 10$, $C_s = N - W + 1$, $SN = 4$, and $S_1 = 3$.

eliminated successively by a multistage cancellation system for the purpose of achieving a better performance. We have showed that the optical-SIC receiver manages to upgrade the performance of the conventional receiver by choosing the best threshold value, the cancellation stage, and the code length. It is important to note that, we could also improve the performance by using other parameters such as the code weight and the correlation values.

4.2 Parallel interference cancelation receiver (PIC)

4.2.1 Principles

The principle of a PIC receiver is based on the estimation of the interference due to all the undesired users. Once the IAM is determined, it is discarded from the received signal before detecting the desired user. We start by detecting all the $(N-1)$ undesired users by a CCR receiver with a threshold level S_T ($0 < S_T \leq W$). Each receiver generates the estimation $\hat{b}_i^{(j)}$ of the undesired user $\# j$ data. This last one is spread by the corresponding code sequence. Then, the reconstructed interference is removed from the received signal. Finally, the data of the desired user are detected with a CCR with a threshold level S_F ($0 < S_F \leq W$) (**Figure 9**) [9].

4.2.2 PIC receiver

The first stage of parallel interference cancelation receiver is a parallel structure whose receivers are all CCR. The signal applied to the second stage is expressed as:

$$\begin{aligned}
 s(t) &= r(t) - \sum_{j=2}^N \hat{b}_i^{(j)} c_j(t) \\
 &= \hat{b}_i^{(1)} c_1(t) + \sum_{j=2}^N \left(b_i^{(j)} - \hat{b}_i^{(j)} \right) c_j(t)
 \end{aligned} \tag{23}$$

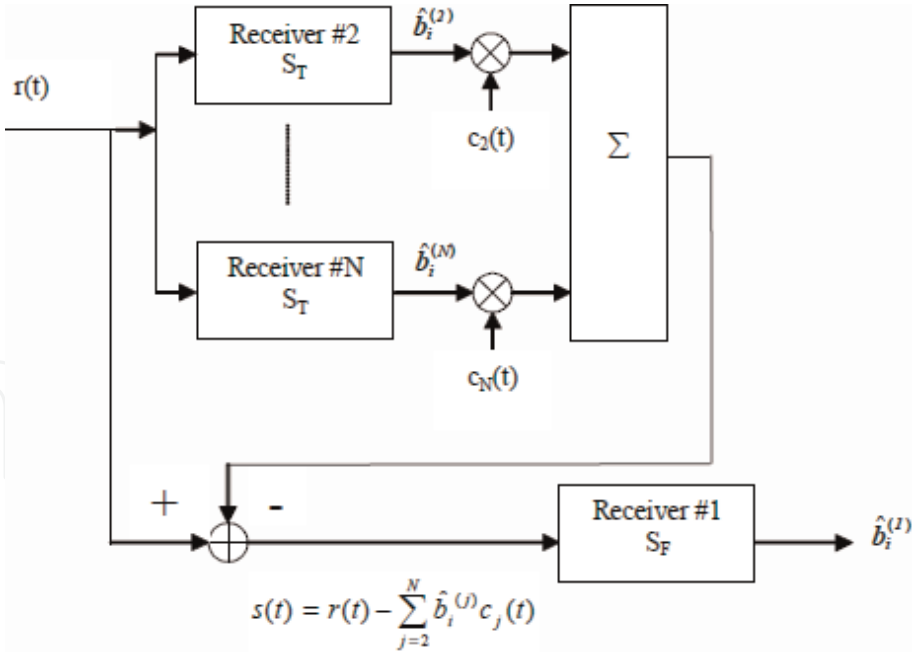


Figure 9.
 Parallel interference cancellation structure.

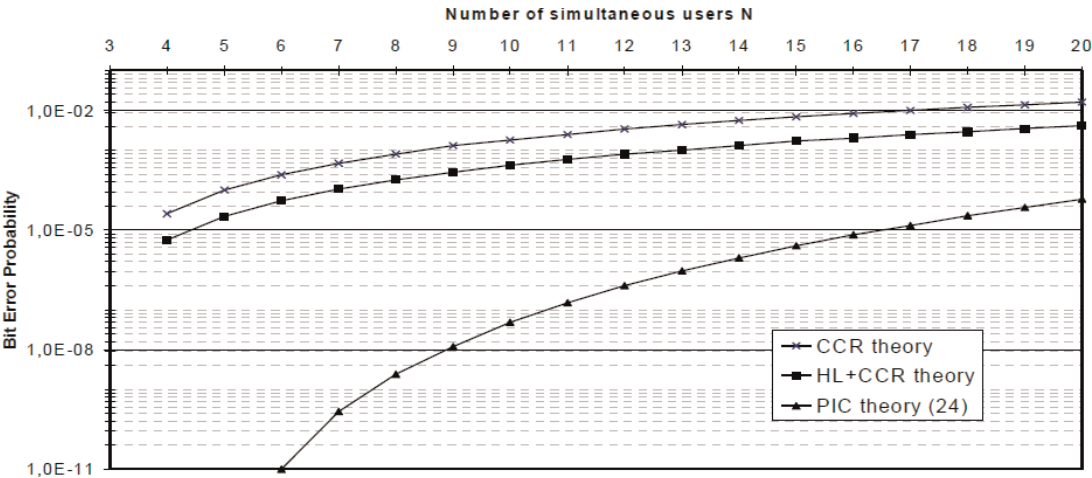


Figure 10.
 BER as a function of the number of simultaneous users $N:F = 121$ and $W = 3$.

where $\left(b_i^{(j)} - \hat{b}_i^{(j)}\right)$ can take two values: “0” or “−1”. So, the second term in Eq. (23) generates negative interference on user #1. Thus, one of the structure originalities is that errors can occur only when the desired user’s sent datum is 1, contrary to CCR.

We have established in [8] that the theoretical expression of the PIC error probability is:

$$P_{ePIC} = (1/2)^N \cdot \sum_{N_1=S_T-1}^{N-1} \sum_{N_2=W+1-S_F}^{N-1-N_1} \binom{N-1}{N_1} \binom{N-1-N_1}{N_2} (P_{IPIC})(1-P_{IPIC}) \left(\frac{W^2}{F}\right)^{n_1} \left(1-\frac{W^2}{F}\right)^{N_1-n_1}$$

$$\text{with } P_{IPIC} = \frac{W^2}{F} \sum_{n_1=S_T-1}^{N_1} \binom{N_1}{n_1} \left(\frac{W^2}{F}\right)^{n_1} \left(1-\frac{W^2}{F}\right)^{N_1-n_1}.$$

(24)

A theoretical comparison of the performances of a CCR, a CCR with an optical hard limiter and a PIC receiver was made according to the number of simultaneous

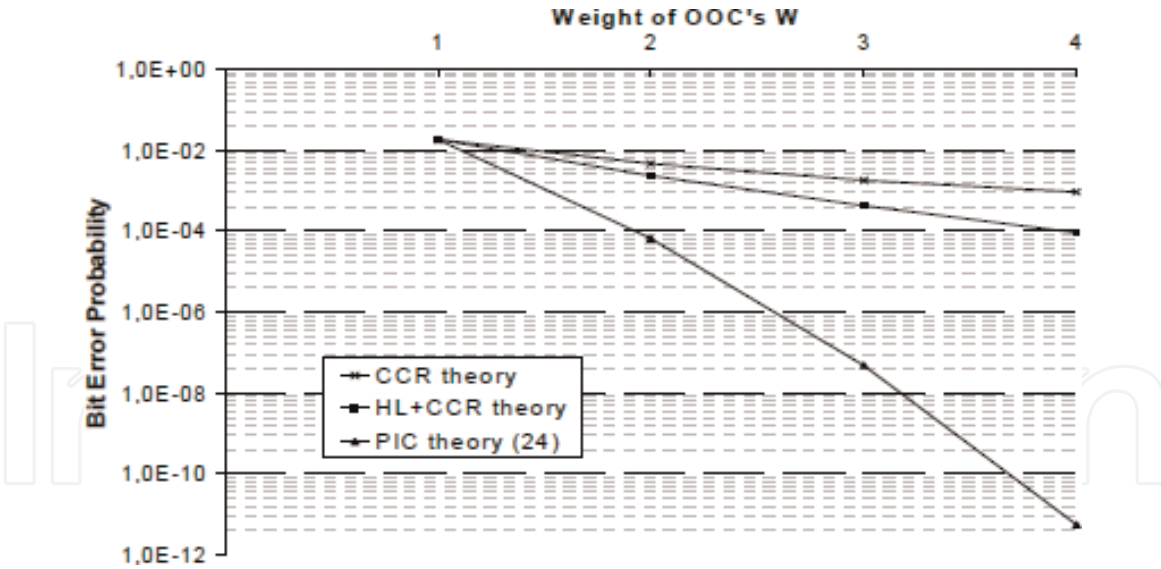


Figure 11.
Bit error probability versus the weight of OOCs $W:F = 121$ and $N = 10$.

users for an OOC ($F = 121$, $W = 4$) code. The bit error rate versus the number of simultaneous users is presented in **Figure 10**. We can observe that the PIC receiver has better BER than the conventional receiver. So, the PIC receiver can support more users than the conventional ones. For example, for BER equal to 10^{-5} , the PIC can support $N = 16$ users, while the conventional receiver with hard limiter can support only $N = 4$ users.

The BER versus the weight W for DS-CDMA systems for a CCR with and without a hard limiter, and a PIC receiver is plotted on **Figure 11**. $F = 121$ and $N = 10$ have been considered as the OOC's code parameters. According to the simulation results, we note that the PIC receiver has a better BER than the traditional ones. Furthermore, at a bit error probability of 10^{-4} , for example, the PIC needs a weight of $W = 2$, while the conventional receiver with hard limiter needs $W = 4$. This configuration of receiver shows so many advantages. First of all, the required power is reduced. In a second time, as the weight is reduced, the number of potential users increases. On the one hand, with $W = 4$, we have 10 available code sequences, so with $N = 10$ users, all the sequences are used. On the other hand, $W = 2$ corresponds to 60 available code sequences; thus, there are 50 unused sequences. Consequently, we can build a system where the sequence codes are definitively assigned to the users, but only 10 of them are allowed to simultaneously communicate.

In order to reduce the effect of the only limitation of an ideal DS-OCDMA system (without taking into account the impact of optoelectronic components), which is multiple access interference (MAI), we have studied the performance of an optical parallel interference cancellation receiver.

This study is based on the analytic expression of the error probability and the system simulation, a comparison with the conventional receiver has been made in each case. The results found prove that the interference cancellation receiver outperforms the ones of conventional receiver.

The PIC receiver could be a suitable receiver in the case of highly loaded networks.

5. Fiber chromatic dispersion effects on OCDMA

In the previous paragraphs, we have showed that the performances of a DS-OCDMA system are degraded by the MAI. However, the MAI is not the only

restriction in the OCDMA optical link networks. In reality, in an optical transmission system, several physical phenomena can degrade the performances of the system [10–12]. The main limitation is due to the chromatic dispersion of the fiber. Indeed, chromatic dispersion leads to optical pulse broadening. This broadening results in overlapping between the pulses, which create the interference inter different chip transmitted over optical fiber, which can affect the system performances. At the output of the optical fiber, it is possible to express the electric field of the j^{th} chip (code) of the l^{th} bit (data) as a function of the in-phase component and quadrature as follows:

$$E_{l,j}^1 = \left(y_{p1}^{l,j} + jy_{q1}^{l,j} \right) + \left(\sum_{i=2}^N y_{pi}^{l,j} + j \sum_{i=2}^N y_{qi}^{l,j} \right) + \left(\sum_{h=-\left[\frac{T-T_c}{2T_c}\right]}^{\left[\frac{T-T_c}{2T_c}\right]} y_{Dp_{j-h}} + j \sum_{h=-\left[\frac{T-T_c}{2T_c}\right]}^{\left[\frac{T-T_c}{2T_c}\right]} y_{Dq_{j-h}} \right) \quad (25)$$

where (y_{pi}, y_{qi}) are the components, respectively, in phase and quadrature of the electric field of the user i^{th} and (y_{Dp}, y_{Dq}) those due to the chromatic dispersion. The first term corresponds to the data of the desired user, the second is the corresponding term to the MAI, and the last is due to the chromatic dispersion. Indeed, the superposition of the MAI term and the term due to the dispersion produce a sufficient power to degrade the system performances.

The propagation distance is usually short in the access networks. For such networks, we deploy the G652 single-mode fiber optics. Therefore, intramodal dispersion can be neglected. Asymmetries and stress distribution in fiber core, which leads to birefringence, cause the polarization mode dispersion (PMD). It affects only long-haul communication systems. Nonlinear effects (Kerr and Raman effects) in optical fiber can degrade the performances of the system, but mainly for long-distance communication. Such nonlinearities are dependent on the signal intensity, which are not significant at the low power. Therefore, for a short access optical link, chromatic dispersion effect is an important factor, which needs to be addressed. For high data rates, the OCDMA technique requires the generation of ultrashort pulses. Indeed, for a given data rate D , the chip rate D_c is expressed as: $D_c = 1/T_c = F.D$. These pulses are sensitive to chromatic dispersion.

To study the impact of chromatic dispersion on the performances of the system, several simulations have been made in the case when there is no dispersion compensation component deployed. The study has been done according to different network parameters and those of the code.

At first, we analyze the performances as a function of the fiber length for a fixed pulse duration $T_c = 1/(F * D) = 2.51 \cdot 10^{-11} \text{ s}$ and the number of active users $N = 5$.

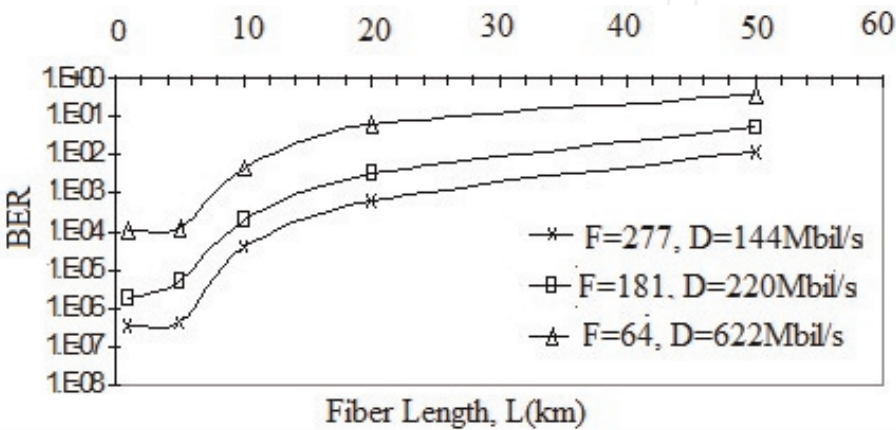


Figure 12.
Variation of BER as a function of fiber length, where $T_c (F,D) = 2.51 \cdot 10^{-11} \text{ s}$ and $N = 5$.

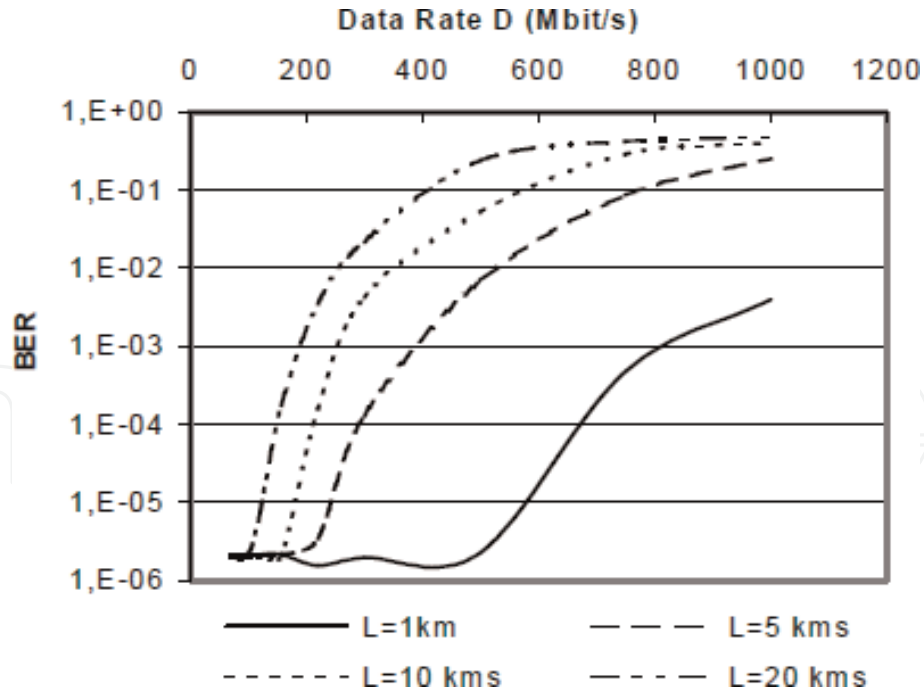


Figure 13.
BER versus data rate D for an OCDMA link with OOC ($F = 181$, $W = 4$) and $N = 5$ active users.

Figure 12 illustrates the variation of the BER as a function of the fiber length for three codes with various F s and D s. It can be noted that the dispersion effect increases as the fiber length increases. However, for this particular chip duration, the dispersion has no impact on the BER for optical fibers shorter than 5 km. On the other hand, when the fiber's length is greater than 5 km, system performance is deteriorated.

In order to complete our study, the BER versus data rate D , for a code length $F = 181$, has been simulated (**Figure 13**). For example, on the one hand, we can observe that the performances of an OOC ($F = 181$, $W = 4$) are not affected by the fiber dispersion up to $D = 600$ Mbits/s for a 1-km-long optical link. On the other hand, for a 20-km-long optical link, the performances are degraded from a data rate $D = 100$ Mbits/s.

The curves indicate that for making the effect of dispersion negligible, without using in the OCDMA link, a dispersion compensated component, we should have a trade-off between OOC code length F and data rate D .

The parametric study has shown that the OCDMA link performances in the access network context are significantly overestimated when the fiber chromatic dispersion is neglected.

6. Conclusion

In this chapter, we studied the DS-OCDMA multiple access technique envisaged for optical communications, in particular in PON access networks. To maintain high rates, the code spreading length should be as low as possible. In this case and for an incoherent system, it has been shown that the IAM multiple access interference, linked to the use of quasi-orthogonal unipolar codes, is very important and does not make it possible to maintain the quality of the link. It is, therefore, necessary to reduce the MAI in order to be closer to the specifications. For this purpose, two structures were studied: the serial interference cancelation (SIC) and the parallel interference cancelation (PIC). We first developed the approximate theoretical expression of the SIC error probability for unipolar codes whose intercorrelation is

equal to 1. We have verified that SIC improves performance with respect to the conventional correlation receiver (CCR). Due to the dependency of a stage on previous ones, the exact theoretical analysis is very difficult to carry out.

Then, the efficiency of the PIC structure for unipolar codes whose intercorrelation is '1' has been investigated.

We have studied theoretically and by simulation the performance of a system using OOC codes, and we have shown that the PIC can significantly improve the performance.

Finally, since IAM is not the only limitation of performance, we have studied the impact of chromatic dispersion. It is demonstrated that chromatic dispersion has a significant negative effect on system performance, which cannot be neglected for systems with a short fiber length and a high data rate. It is reported that system performance can be significantly overestimated if chromatic dispersion is ignored.

Appendices and nomenclature

ADSL	asymmetric digital subscriber line
CCR	conventionnal correlation receiver
CDMA	code-division multiple access
DS-CDMA	direct sequence-CDMA
FDMA	frequency-division multiple access
FFH-CDMA	fast FH-CDMA
FTTB	fiber to the building
FTTC	fiber to the curb
FTTH	fiber to the home
HL	hard limiter
MAI	multiple access interference
OCDMA	optical CDMA
OOC	optical orthogonal code
PIC	parallel interference cancelation receiver
PMD	polarization mode dispersion
PON	passive optical network
SIC	successive interference cancelation receiver
TDMA	time-division multiple access
WDMA	wavelength-division multiple access

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