Direct-Sequence Code Division Multiple Access: From radio communications to optical networks

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Abstract

A direct sequence optical code division multiple access technique is investigated. This paper introduces, first, the principles definitions of Code Division Multiple Access in radio communications. After that, the performances of Optical Code Division Multiple Access are evaluated in association with a realistic amplified optical channel model.

To determine the performances obtained by this combination, different detection methods are investigated in an Optical CDMA system. Threshold and multi-user detections are developed in association with Optical Orthogonal Codes: OOC and Prime Sequences: PS, specially designed to be adapted to fiber optic channel.

Key words: Code division multiple access, Radiocommunication, Direct sequence spread spectrum, Optical telecommunication, Optical fiber transmission, Gaussian channel, Amplification, Coding, Background noise, Signal detection, Error rate.

ACCÈS MULTIPLE PAR RÉPARTITION DE CODES À SÉQUENCES DIRECTES : DES COMMUNICATIONS RADIOFRÉQUENCES AUX RÉSEAUX OPTIQUES

Résumé

Dans cet article, une étude des techniques d'accès multiple par répartition de code (CDMA) à séquences directes est réalisée. En premier lieu, les principales définitions du CDMA utilisé dans les systèmes de radio communications sont données. Par la suite, les performances du CDMA optique sont évaluées en y associant un modèle réaliste de canal optique amplifié.

Afin de déterminer les performances obtenues par ce modèle, différentes méthodes de détection ont été mises en œuvre dans le système CDMA optique, citons comme exemple le détecteur à seuil et le détecteur multi-utilisateur. De plus des codes spécifiques au CDMA optique sont évalués et associés à notre modèle de canal, parmi lesquelles les code optiques orthogonaux (OOC) et les séquences premières (PS).

Mots clés : Accès multiple code, Spectre séquence directe, Télécommunication optique, Transmission fibre optique, Canal gaussien, Amplification, Codage, Bruit fond, Détection signal, Taux erreur.

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I. INTRODUCTION

For few years now, great attention is paid to multi-access techniques for the optical communications such as OCDMA (Optical Code Division Multiple Access). The need of faster and more reliable communication systems has been felt and the sharing of the huge optical bandwidth between users needs adapted access techniques. In order to meet these needs, OCDMA is an attractive solution.

Code Division Multiple Access is often used in radio communication systems like IS 95 or UMTS radio mobile standards. CDMA allows to each subscriber to use a specific codeword (or a code sequence) to modulate its data stream. The resulting coded sequences of the users, are superimposed, transmitted through a communication channel and at least, detected by the appropriate receivers.

In radio communication systems, bipolar sequences are used as codes to modulate data streams. These sequences are composed by [1, –1] chips and are strictly orthogonal in the synchronous case. However, this orthogonality may be degraded in asynchronous systems.

In optical communications, bipolar sequences cannot be used to code data streams due to square law of optical detection. To applied CDMA technique to the optical channel, specific optical codes were generated. These accommodate with a low cross correlation level. In consequence, sparse sequences are used according that the apparition of chips "0" and "1" is not equiprobable.

Different optical channel models using Poissonian signal distributions associated to OCDMA were previously investigate [1-3], however, these configurations do not take into account receiver thermal noise and amplification noises introduced by today amplified optical channel.

Amplification is not mandatory in "point to point" transmission systems that operate at a low bit rate and without using multiplexing techniques thanks to the low transmission losses of the fiber. However, in the particular case of Optical CDMA, the couplers introduce additional losses and the total power sharing implies the use of optical amplifier.

The aim of this paper is to evaluate the performances of direct-sequence optical CDMA technique by using a Gaussian noise amplified optical channel and by taking into account the different noises introduced by the optical channel.

This paper gives, first, definitions for different multi-access techniques and presents a short remind of CDMA in radio communication systems. Thereafter, different detection methods are investigated using specific optical codes like Optical Orthogonal Codes (OOC) and Prime Sequences (PS). At least, direct-sequence OCDMA technique associated to a realistic optical amplified Gaussian channel model, taking into account the most important noises generated during the signal transmission and amplification is developed. The overall system performances are, final, analyzed and discussed.

II. MULTI-ACCESS TECHNIQUES

Initially, the "point to point" communication systems allocate to each pair transmitter / receiver a specific communication channel. The aim of multi-access techniques is to improve the capacity, and optimize the use of the available transmission channel. Indeed, the recent multiplexing methods allow to different transmitters to send their data streams through the same communication channel by limiting the effects of the users interferences. The transmitters sharing the same transmission channel can be time, frequency, wavelength or code multiplexed [4-6].

II.1. TDMA technique

In Time Division Multiple Access (TDMA) technique, the transmitters share the same bandwidth but emit their messages on different time slots in order to avoid users data streams interferes as displayed in Figure 1.

The time slots are allowed in round-robin fashion. However, other allocation methods, such as ALOAH, may be used.

TDMA may be used not only to multiplex collocate messages sources but also by geographically separated users who have the ability to maintain time synchronization. Moreover, no frequency control between the different users is required.

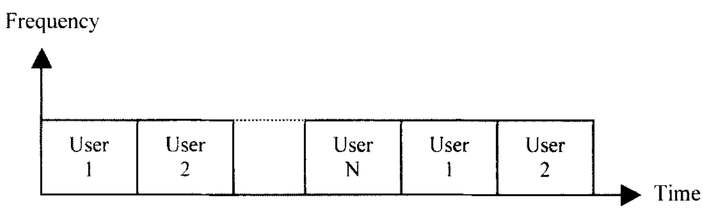

FIG. 1 – Time Division Multiple Access technique.

Accès Multiple par Répartition en Temps.

II.2. FDMA and WDM techniques

Frequency Division Multiple Access (FDMA) and Wavelength Division Multiplexing (WDM) techniques follow the same principles. The FDMA term is employed in radio frequency communications field and WDM is used in optical communications. In FDMA, we assign to each transmitter / receiver a specific carrier frequency, so that the resulting spectra do not overlap. In the same way, WDM is associated to optical communications. Lasers of various wavelengths can be transmitted along a single fiber, and each laser can be modulated by its own set of radio-frequency signals. So, the received signals are distinguished by their different wavelengths.

The principal difference between WDM and FDMA is that in WDM systems, the wavelengths are separated by an all-optical filter before detection.

Figure 2 and Figure 3 show, respectively, how FDMA and WDM operate.

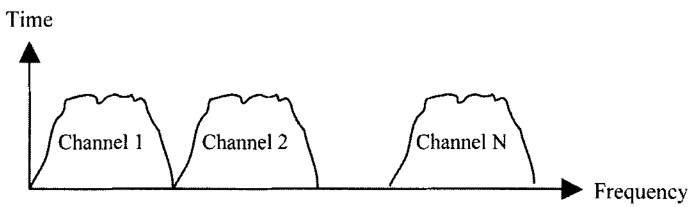

FIG. 2 – Frequency Division Multiple Access technique.

Accès Multiple par Répartition en Fréquence.

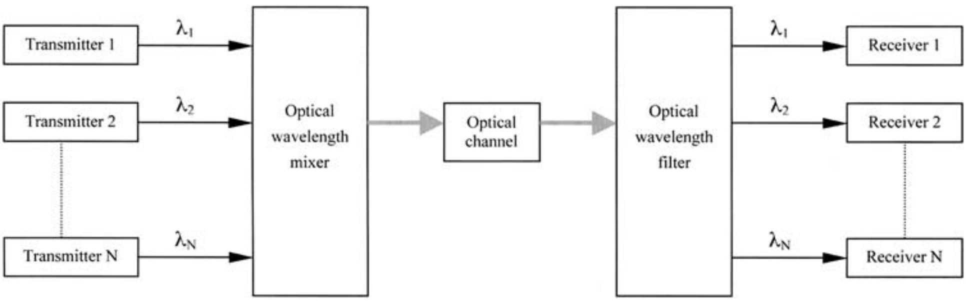

FIG. 3 – Operation principle of a WDM system.

Principe de fonctionnement d'un système WDM.

These two multiplexing techniques do not need time synchronization between the different uses.

II.3. CDMA technique

The multiplexing capacity in Code Division Multiple Access is intrinsic to our ability to generate an appropriate code group. Indeed, in the previous multiplexing methods, multiplexing capacity is limited by the physical medium (available wavelength, bandwidth, available time slots...)

In CDMA, the users can emit their data stream at any time and in any frequency. A specific code is associated to each user. This code is used to recover the message emitted by a particular transmitter and distinguish it among the other users data signals.

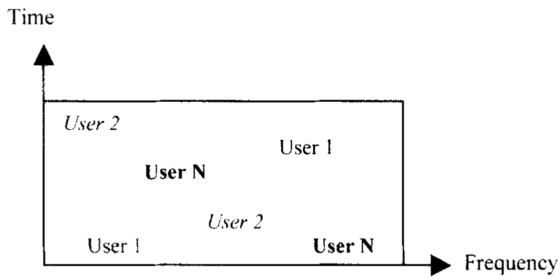

FIG. 4 – Code Division Multiple Access technique.

Accès Multiple par Répartition par Codes.

III. RADIOFREQUENCY COMMUNICATIONS CDMA DEFINITIONS

The first applications of Code Division Multiple Access were realized in radio frequency field. CDMA spreads the message to a relatively wide bandwidth by using a unique code that reduces the interferences, enhances system proceedings and differentiates users.

A group of code sequences permits to multiplex several transmitters. For CDMA, the pulses that compose a code sequence are named "chips", this to differentiate between data bits and the pulses that constitute a given code sequence associated to a given data bit.

The two principals CDMA models, in radio frequency communications, are: direct-sequence CDMA and frequency hopping CDMA [5-7]. These models are detailed below.

III.1. Bipolar code characteristics

In radio frequency communication systems, the codewords used by a code division multiple access technique are strictly orthogonal, since they are composed by pulses [–1, 1] and have a cross correlation function equal to zero in the synchronous case. Using orthogonal sequence as codewords permits to reduce the effect of Multi-Access Interferences. Indeed, Walsh functions are an example of bipolar codes used by these systems [7], so let x_1 and x_2 be a Walsh codewords:

$$CC_{x_1,x_2}(t) = \int_0^T x_1(t)\, x_2(t) dt \tag{1}$$

where T represent the bit period. The definition and algorithm generation of Walsh functions and other orthogonal sequences can be found in [7]. The pulses that compose a code sequence are named "chips" to be differentiated from the "bits" that compose the information signal. In the case of radio frequency communication systems, multi-access interferences (MAI) are generated in the asynchronous configuration since the codes, in this case, cannot be orthogonal. It will be shown in the next section that optical code characteristics are very different than codes used in radio frequency systems since these last are bipolar and strictly orthogonal in the synchronous configuration.

III.2. Direct-Sequence CDMA

Direct sequence CDMA is automatically associated to a spread spectrum communication system. The message is first modulated by traditional amplitude, frequency or phase techniques. A pseudo noise signal is then used as a code sequence to spread the modulated waveform over a relative wide bandwidth. The direct sequence spread spectrum may be obtained by multiplying the message signal *x(t)* by a pseudorandom noise *pn(t)*. Figure 5 gives an example of this modulation.

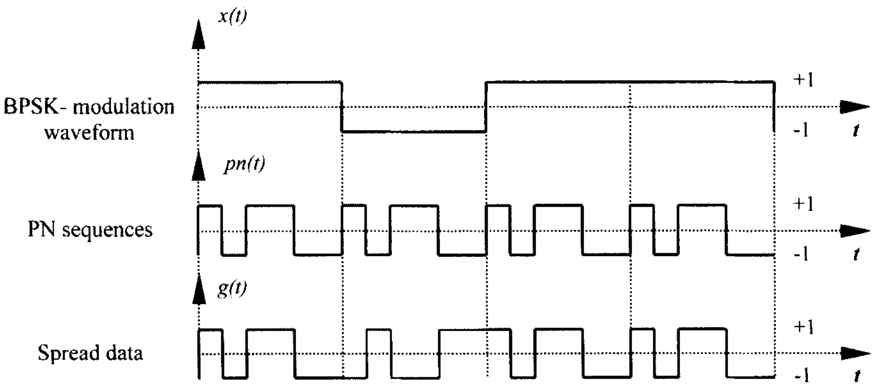

FIG. 5 – Direct Sequence CDMA modulation.

Modulation CDMA à Séquence Directe.

The signal message maybe also coded by the code sequences and after that, modulated by a BPSK (for example) waveform.

III.3. Frequency Hopping CDMA

In frequency hopping spread spectrum, the chips, that compose the code sequence assigned to a given user, are modulated in frequency. Each of the N chips corresponds to a sinusoidal waveform whose frequency is chosen pseudo-randomly from a given set of frequencies.

In addition to the appropriate codewords choices, the frequency hopping model may be reduce the multi access interferences created by the users messages.

Frequency hopping model is considered as slow when several data bits are transmitted at the same frequency. In opposite, frequency hopping model is considered as fast when the chips, in one bit, are transmitted at different frequencies. Figure 6 shows how slow frequency hopping CDMA operate.

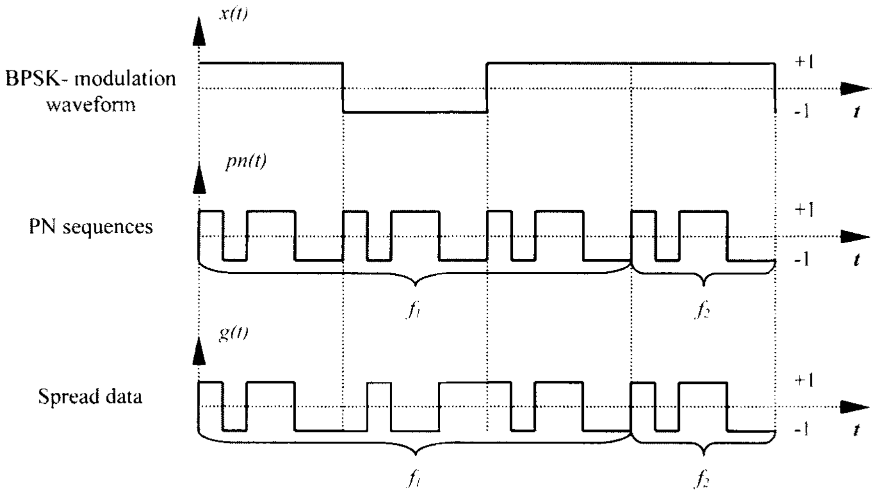

FIG. 6 – Frequency Hopping CDMA modulation.

Modulation CDMA à Sauts de Fréquences.

III.4. Benefit of spread spectrum technique

Spread spectrum modulation and CDMA technique allow several users to share the radio frequency spectrum, thus the received signal becomes the sum of the k user signals and noise. The receivers recover the message signal by dispreading the received signal. It does that by synchronizing its correlator to a specific spreading sequence that is unique to the user and different from those of other users. As a result, the other user signals appear as noise [5].

IV. OPTICAL CDMA

In Optical CDMA, we retrieve the same principles as radio frequency CDMA even if we have to adapt these techniques to the specificity of optical transmission channel.

The aim of Optical Code Division Multiple Access is to take benefit of radio frequency communication CDMA technique to share the huge optical bandwidth. Specific constraints associate to the optical communication systems have to be taken into account while preserving the advantages brought by this technique, principally:

- Improvement of multiplexing capacity.
- Resource sharing
- Asynchronous emission of the subscribers
- Cost reduction of network installation

Figure 7 shows the principle of optical CDMA communication system.

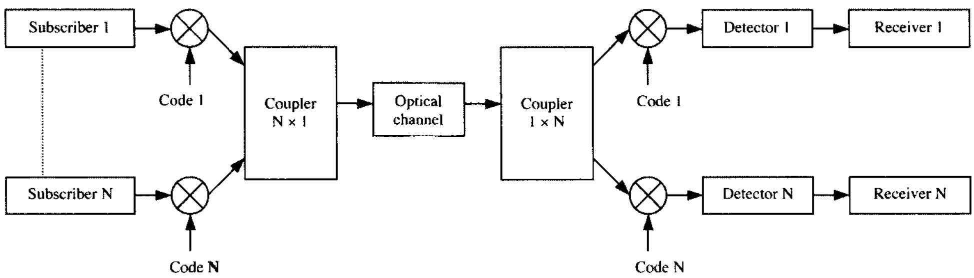

FIG. 7 – Optical CDMA communication system.

Système de communication CDMA Optique.

There are two categories in Optical CDMA, the first one use coherent detection (heterodyne detection), and the second one use non-coherent detection (direct detection).

In the coherent detection orthogonal codes (Gold sequences, Pseudo-Noise sequences...) can be used. But it is important to note that it is difficult, in optical communication, to preserve the signal phase during the transmission through the optical channel. Even if some experimental set-ups exist using coherent Optical CDMA, these systems are complex and expensive to be implemented since they need a special set up to manage the phase dispersions of the transmitted CDMA signal.

The non-coherent CDMA present a more attractive solution even if strict orthogonal sequence cannot be used. For the direct detection CDMA applications, special optical sequences are conceived.

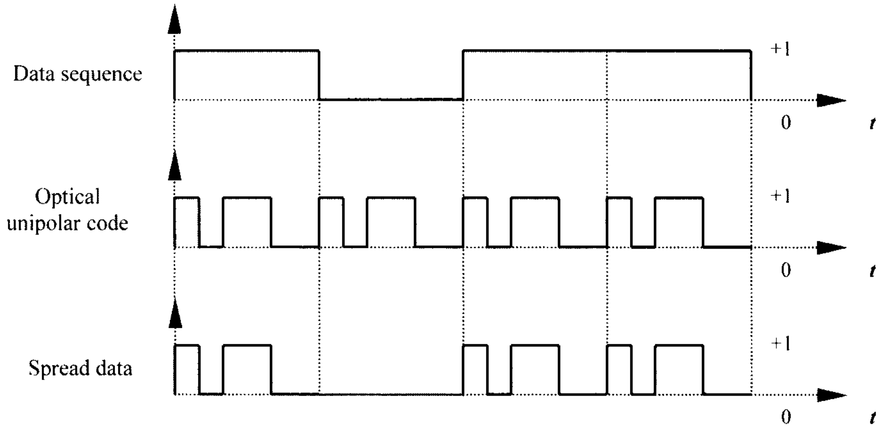

FIG. 8 – Optical Direct Sequence CDMA modulation.

Modulation CDMA Optique à Séquence Directe.

V. OPTICAL CODES

To understand how non-coherent CDMA works, it is necessary the study the optical codes which are used by this method [8-14].

Optical codes were generating to be used in association with optical channel. Indeed, as it is said previously, optical transmission channel do not conserve signal phase, so bipolar codes, which may be orthogonal, cannot be used. Consequently, unipolar sequences are used as codewords to modulate and spread data sequences, as it is shown in Figure 8.

A unipolar or "optical" codeword is principally defined by its length L which is represented by the number of chips in the code sequences, its weight ω which is represented by the number of chips equal to one and its multiplexing capacity N which represents the number of users that can be multiplexed Among these unipolar codes, Optical Orthogonal Codes (OOC) and Prime Sequences (PS) are the most important. Both OOC and PS respect the same auto and cross correlation constraints. These codes are divided into two groups since they have different construction algorithms.

V.1. Optical Orthogonal Codes (OOC)

1 – For each $x = (x_n)$:

$$|AC_{x,x}(m)| = \left|\sum_{n=0}^{M-1} x_n x_{n+1}\right| = \begin{matrix} \omega & \text{for } m = 0 \\ \leq \lambda_a & \text{for } 1 \leq m \leq L-1 \end{matrix} \tag{2}$$

This condition refers to the auto-correlation constraint.

2 – For each $x = (x_n)$ and $y = (y_n)$

$$|CC_{x,y}(m)| = \left|\sum_{n=0}^{M-1} x_n y_{n+1}\right| \leq \lambda_c \quad \text{for } 1 \leq m \leq L-1 \tag{3}$$

This condition refers to the cross-correlation constraint.

Table I gives some examples of OOC codes [8-9]:

TABLE I. – Example of OOC constructions.

Exemple de la construction de OOC.

N	L	ω	$C_i = \{b_1^{(n)}, b_2^{(n)}, \ldots b_l^{(n)} \ldots\ldots\ldots, b_L^{(n)}\}$
3	21	3	$C_1 = \{1, 2, 6\}$; $C_2 = \{1, 3, 9\}$; $C_3 = \{1, 4, 11\}$
2	29	4	$C_1 = \{1, 2, 8, 12\}$; $C_2 = \{1, 3, 6, 15\}$
4	57	4	$C_1 = \{1, 2, 12, 25\}$; $C_2 = \{1, 5, 22, 25\}$; $C_3 = \{1, 4, 20, 29\}$; $C_4 = \{1, 8, 16, 28\}$

Knowing that $b_l^{(n)}$ represent the "1" chips positions in a code sequence associates to the i$^{\text{th}}$ user.

V.2. Prime sequences (PS)

Prime sequences (PS) were constructed to resolve some problems contiguous to the OOC [13-14], mainly:

– Multiplexing capacity.

– Code length.

Prime Sequences permit to improve the multiplexing capacity and to reduce code length while respecting the same OOC constraints, and this by using a simple algorithm presented above.

Let p be a prime number and i, j two integers included between 0 and $(p - 1)$. S_i represents sequences, which are conceived by the following rule:

(4)
$$\begin{cases} S_i = (s_{i,0}, s_{i,1}, \dots\dots\dots, s_{i,p-1}) \\ s_{i,j} = (i, j) \bmod (p) \end{cases}$$

From the $S_{i,j}$ sequences, a group C_i of prime codes will be generated as follow:

(5)
$$\begin{cases} C_i = \{c_{i,0}, c_{i,1}, \dots\dots, c_{ij} \dots\dots c_{i,N-1}\} \\ c_{i,k} = 1 \quad \text{for} \quad k = s_{i,j} + j.p \\ c_{i,k} = 0 \qquad\qquad \text{otherwise} \end{cases}$$

With this construction, it is possible to generate prime codes with the following characteristics:

– $N = p$: Number of users.
– $\omega = p$: Weight of the code sequence.
– $L = p^2$: Length of the code sequence

The table below gives an example of prime sequences generated by the rules presented above. In this example $p = 5$:

TABLE II. – Example of prime sequences generated for $p = 5$.

Exemple de la génération de séquences première pour $p = 5$.

i	S_i	C_i
0	00000	10000 10000 10000 10000 10000
1	01234	10000 01000 00100 00010 00001
2	02413	10000 00100 00001 01000 00010
3	03142	10000 00010 01000 00001 00100
4	04321	10000 00001 00010 00100 01000

According to the information theory, it is possible to show if Prime Sequences ca be used as a code sequences Indeed, a code structure is considered to be perfectly effective if zeros and ones that constitute the output-coded signal have the same occurrence probability i.e.: $P_s(0) = P_s(1) = 0.5$

Let L, ω and N be, respectively, code length, code weight and number of users. $D = \frac{\omega}{L}$ represents the code sequence density and $P_0 = P_1 = 0.5$ represents the data occurrence probability.

For the particular case of Prime Sequences, $L = p^2$, $\omega = p$ and $N = p$, the occurrence probabilities of ones and zeros in the user signal are given by:

(6)
$$\begin{cases} p(1) = \frac{1}{2}D = \frac{\omega}{2L} = \frac{1}{2p} \\ p(0) = 1 - \frac{\omega}{2L} = 1 - \frac{1}{2p} \end{cases}$$

The output signal is the sum of N user coded sequences. Consequently, the occurrence probabilities of "0" and "1" are given by:

(7)
$$\begin{cases} p_s(0) = \left(1 - \frac{\omega}{2L}\right)^N = \left(1 - \frac{1}{2p}\right)^p \\ p_s(1) = 1 - \left(1 - \frac{\omega}{2L}\right)^N = 1 - \left(1 - \frac{1}{2p}\right)^p \end{cases}$$

Knowing that

$$e = \lim_{n \to \infty} \left(1 + \frac{1}{n}\right)^n$$

(8)
$$\begin{cases} p_s(0) = \left(1 + \frac{1}{n}\right)^{\left(\frac{-n}{2}\right)} = \frac{1}{\left(1 + \frac{1}{n}\right)^n} \\ n = -2p \end{cases}$$

(9)
$$\begin{cases} p_s(0) = \frac{1}{\sqrt{e}} = 0.6065 \\ p_s(1) = 1 - p_s(0) = 0.3935 \end{cases}$$

V.3. Optical Codes Constraints

The optical codes described above present two important limitation

V.3.1. Multiplexing Capacity

In the case of radio frequency communication systems, the number of users that can be multiplexed by an orthogonal group codes is equal to the length of the codeword ($N = L$) in the synchronous case

In the case of optical CDMA systems, the need of a limited cross correlation function (which is non equal to zero) induces a limited multiplexing capacity.

For OOC: $N \leq \frac{L - 1}{\omega(\omega - 1)}$ [8-9]

For PS: $N \leq \sqrt{L} = \omega$

V.3.2. Optical CDMA Signal Bandwidth

For all CDMA communication systems, the CDMA signal bandwidth is given by $B_s = \dfrac{1}{2T_c}$ where T_c is the chip duration. In radio frequency communication systems, this bandwidth can be expressed by:

$$B_s = \frac{1}{2T_c} = \frac{1}{2T_b}$$

$$B_s = \frac{N}{2T_b} = \frac{1}{2}NR_b$$ with $N = L$ and $R_b = \dfrac{1}{T_b}$, where R_b is the bit rate associated to each user.

The optical CDMA signal bandwidth is lager than the radio frequency one, since the code lengths associated to optical systems are more important. In this case the signal bandwidth is given by

For OOC: $B_s = \dfrac{1}{2T_c} = \dfrac{1}{2T_b} = \dfrac{1}{2}[\omega(\omega-1)N_{\max} - 1]R_b$ with $N_{\max} = \dfrac{L-1}{\omega(\omega-1)}$

For PS: $B_s = \dfrac{1}{2T_c} = \dfrac{L}{2T_b} = \dfrac{1}{2}N_{\max}^2 R_b$ with $N_{\max} = \sqrt{L} - \omega$

Figure 9 shows the Optical CDMA signal bandwidth versus the number of user and for different data bit rate.

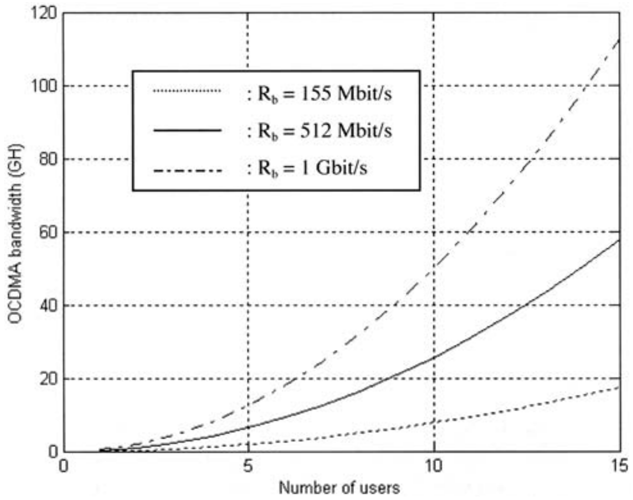

FIG. 9 – Optical CDMA signal bandwidth versus the multiplexing capacity.

Bande passante du signal CDMA optique en fonction de la capacité de multiplexage.

VI. DETECTION METHODS

In this section, two detection methods, that can be integrate in Optical CDMA systems, are presented. Threshold detector is considered as a hard decision detector, in opposite of multi-user one that is associated to a soft decision method [15]. To understand how these two detection systems work, there is a need to detail how an optical CDMA signal is obtained.

VI.1. OCDMA Signal

In Optical CDMA technique, optical codes are used to modulate the data sequence coming from the different users. The signal resulting from this multiplexing technique can be given by:

(10)
$$S_{CDMA}(t) = \sum_{n=1}^{N} b_n C_n (t - \tau_n)$$

b_n : the data sequence corresponding to the nth user.

$C_n (t - \tau_n)$: the code sequence allowed to the nth user.

τ_n : the delay associated to the nth user. It is considered that for the first user $\tau_1 = 0$.

(11)
$$C_n(t) = \sum_{j=1}^{L} c_{n,j} d_j (t - jT_c)$$

L: Length of the code sequence

$c_{n,j}$: The jth chip position associated to the nth codeword.

T_c: Chip period

VI.2. Threshold Detection

At signal reception, the received signal $\vec{r}$ is multiplied by a specific code sequence associated to a desired receiver. After that, the detector calculates the autocorrelation function of the resulting sequence and compares it to a fixed threshold. If the autocorrelation level is higher than this threshold it is decided in favor of bit "1", else it is decided in favor of bit "0". Figure 10 shows a threshold (mono-user) detector.

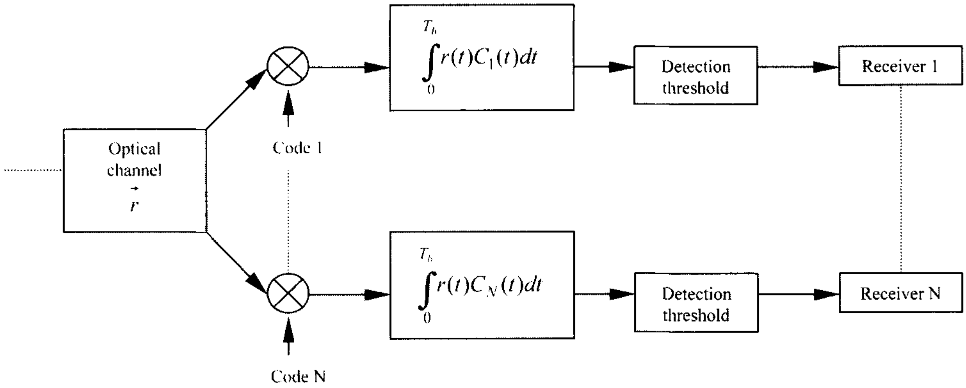

FIG. 10 – Threshold detection system.

Système de détection à seuil.

At the input of threshold detector $r(t) = S_{CDMA} + ON$, where ON can be considered as an additive Optical Noise.

Consequently, if it is considered that the first user transmits the useful signal, the detected signal can be expressed by:

$$y_1(t) = \int_0^{T_b} r(t)\, C_1(t)\, dt$$

(12)
$$= \int_0^{T_b} (S_{CDMA}(t) + ON)C_1(t)dt$$

$$= \int_0^{T_b} \left(\sum_{n=1}^{N} b_n C_n(t) + ON\right)C_1(t)dt$$

(13)
$$y_1(t) = \int_0^{T_b} b_1(C_1(t))^2 dt + \int_0^{T_b} \left(\sum_{n=2}^{N} b_n C_n(t) + ON\right)C_1(t)dt$$

where MAI are Multi Access Interferences

The threshold detector operates without taking into account the effect of presence of the other transmitter on the desired decoded data sequence.

Remark: Threshold detection methods can be implemented by both electrical and optical components.

VI.3. All Optical Encoder/Decoder Systems

All optical detection systems operate with threshold detection technique. Their principal advantage is to work at higher bit rate than electrical detection systems.

Remark: It is important to note that all-optical detection systems permit to employ photo-detectors at the users bit rate, in opposite of electrical detection systems that need to use photo-detectors at chip rate. Indeed, the decoding in all-optical systems is doing before detection and the needed bandwidth corresponds to the users bit rate.

VI.3.1. Parallel Delay Lines Encoder/Decoder

The encoder and decoder presented in figures 11 and 12 respectively can be introduced in the optical CDMA communication system presented in figure 7 (Part 4)

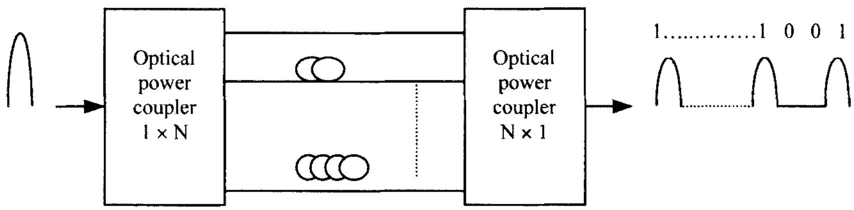

FIG. 11 – Encoder by parallel delay lines.

Codeur utilisant des lignes à retard parallèles.

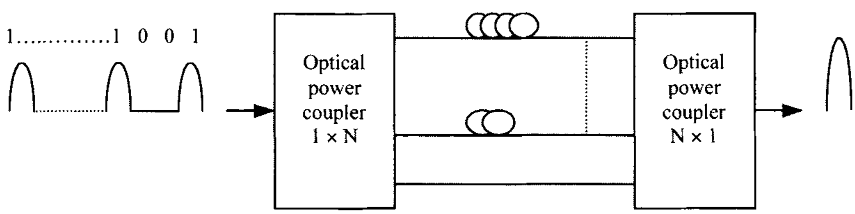

FIG. 12 – Encoder by parallel delay lines.

Codeur utilisant des lignes à retard parallèles.

The principle of this system is to introduce a pulse (bit information) on the $(1 \times N)$ coupler. This pulse is split on ω pulses and delayed to generate an optical code of length L. The resulted pulses are transmitted by the optical channel and decoded by a matched system (figure 12)

Even if the parallel delay lines encoder/decoder can be easily implemented, it present several drawbacks:

– The power of the pulses at the power coupler input is split into ω, so it is necessary to use an optical amplifier.

– The couplers generate power losses.

VI.3.2. Fiber Bragg Gratings (fbg) Encoder / Decoder

Figures 13 and 14 present a Fiber Bragg Gating (FBG) encoder and decoder, respectively.

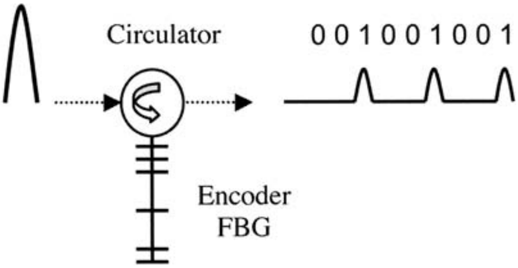

FIG. 13 – Fiber Bragg Grating (FBG) used as CDMA encoder.

Fibre à Réseaux de Bragg utilisée comme codeur CDMA.

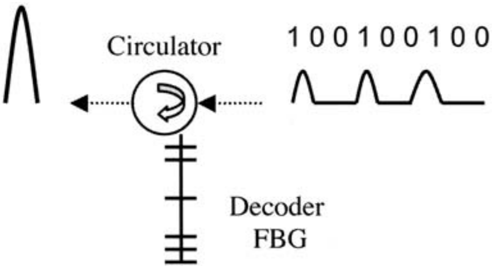

FIG. 14 – Fiber Bragg Grating (FBG) used as CDMA decoder.

Fibre à Réseaux de Bragg utilisée comme décodeur CDMA.

This configuration can also be integrated in the optical CDMA transmission system presented in figure 7 (Part 4). An optical pulse, (data bit), is transmitted by a circulator to the FBG. This FBG generates, by reflection, an optical codeword. The optical channel transmits the generated sequences and the matched decoder permit to recombine the chips and recover the data bits that compose the information sequences. Some examples of using FBG as optical CDMA encoders/decoders are given in [16-18].

The concatenation of Bragg gratings that have the same length generate chip pulses with the same amplitude if the modulation index of the Bragg reflectors are different [17].

The disadvantages of using FBG in CDMA applications are appreciably the same as parallel delay lines with the difference that FBG are considered as integrated systems and can be easily implemented.

VI.4. Multi-User Detection

To recover the messages sent by the transmitters, this detector observes simultaneously the different coded data sequences transmitted [7]. Figure 15 shows multi-user detector.

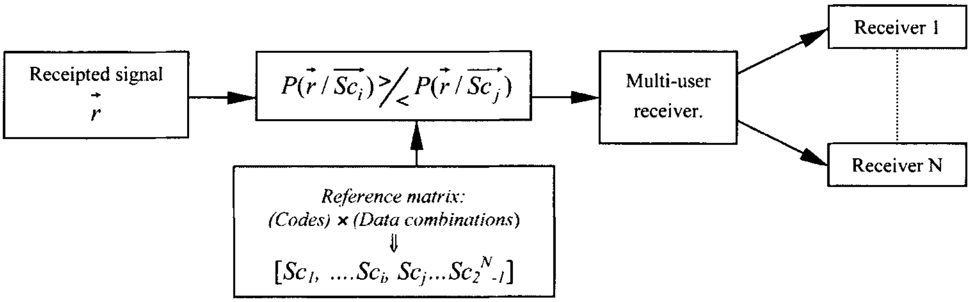

FIG. 15 – Multi-user detection system.

Système de détection multi-utilisateurs.

In this detector, the received signal will be compared to a reference matrix. This one results from the multiplication of all available codewords by different data sequence combinations. The data sequence combination matrix represents all possible data bit states that all the users can take at the same time as it is shown in the example given bellow.

The comparison between the received signal and reference sequences is done by calculate the probability $P(r(t)/Sc(t))$ and decide in favor of sequence $Sc(t)$ that gives the better probability. When a sequence $Sc(t)$ is selected, its corresponding data combination is transmitted to the multiuser receiver and this one dispatches the information to each concerned receiver.

$$ref\_mat = [data\_combination] \times [C_1(t);\ C_2(t);\ \ldots\ldots C_N(t)]$$

$$= [Sc_1(t);\ Sc_2(t);\ \ldots\ldots\ Sc_{2^N-1}]$$

(14) $$Dist = \min(d^2) = \min(|r(t) - Sc_k(t)|^2) \quad 1 \le k \le 2^N - 1$$

Below, an example of a reference matrix is presented. In this case, it is considered that three users emit simultaneously and prime sequences are used as codewords.

$$reference\_matrix = [data\_combination] \times (code\_sequences)$$

$$reference\_matrix = \underbrace{\begin{bmatrix} 00001111 \\ 00110011 \\ 01010101 \end{bmatrix}^t}_{Data\_combinaison} \times \underbrace{\begin{bmatrix} 100100100 \\ 100010001 \\ 100001010 \end{bmatrix}}_{Code\_sequences} = \underbrace{\begin{bmatrix} 000000000 \\ 100001010 \\ 100010001 \\ 200011011 \\ 100100100 \\ 200101110 \\ 300111111 \end{bmatrix}}_{reference\_matrix}$$

Consequently, the detector compares the probabilities $P(\vec{r}/\overrightarrow{Sc_i})$ and $P(\vec{r}/\overrightarrow{Sc_j})$decides in favour of data sequence witch corresponds to the higher probability $\vec{r}$, $\overrightarrow{Sc_i}$ and $\overrightarrow{Sc_j}$ represent, respectively, the received signal and reference matrix sequences. The implementation of multi-user detector cannot be realised in the actual state of the art because of the complexity evaluation of the system. Indeed, to obtain a multi-user detection for 10 users, we need 15 Giga operations. So in real communication systems, only threshold detectors are employed.

VII. GAUSSIAN OPTICAL AMPLIFIED CHANNEL MODEL

Figure 16 shows the optical amplified channel model associated to OCDMA. A quasi-equi-probable sequence is generated by the superposition of coded data sequences. This signal is transmitted, amplified by the optical channel and filtered. The detector recovers the coded data sequence. The optical channel is considered as Gaussian since the field in this channel has a Gaussian behavior.

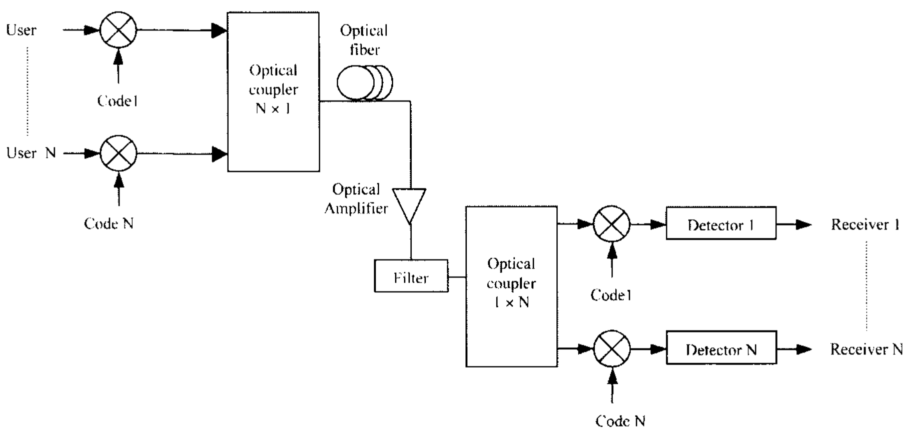

FIG. 16 – Simplified optical amplified channel model.

Modèle de canal optique amplifié.

The signal at the input of the detector has a mean photocurrent value equal to:

$$\bar{i} = GR\overline{P}$$

and three principal noise components are introduced [16]. The signal against noise beating is expressed by the variance:

$$\sigma^2_{s-N} = 4RS_N\,\bar{i}B_e \qquad \text{with} \quad S_N = F(G-1)\,\frac{h\nu}{2}$$

The noise against noise beating is given:

$$\sigma^2_{N-N} = 2mR^2S_N^2\left(B_o - \frac{B_e}{2}\right)B_e$$

The thermal noise is given by:

$$\sigma_T^2 = \frac{4kT_e}{R_L}\,B_e$$

The different parameters that characterize the optical amplified channel are given in Table III.

TABLE III. – Numerical values of optical amplified channel parameters.

Valeurs numériques des paramètres intervenants dans le modèle du canal optique amplifié.

Parameters	Symbols	Values
Optical bandwidth (MHz)	B_o	
Optical power at the optical ampliifer input (dBm)	P	
Extinction ration at the receiver	r	0.1
Photo detector responsivity (A/W)	R	1
Optical noise factor (dB)	F	6
Polarization mode number	m	2
Equivalent temperature (K)	T	600
Boltzmann constant (J/K)	k	1.38×10^{-23}
Load resistance (Ω)	R_L	50
Optical amplifier gain (dB)	G	30
Electrical bandwidth (Mhz)	B_e	80
Optical frequency (Thz)	ν	200
Planck constant (J.s)	h	6.63×10^{-34}

VIII. RESULTS AND PERFORMANCES

The results presented in this paper evaluate threshold detection in association with optical CDMA systems using a Gaussian approximation to detect the optical amplified signal [16].

The means and variances of chips “1” and “0” are given by

$$(15)\qquad \begin{cases} \overline{i_1} = GR\overline{P_1} \quad \text{et} \quad \overline{i_0} = rGR\overline{P_1} \\ \sigma_{1,0}^2 = 4S_N R\overline{i_{1,0}}B_e + 2mR^2S_N^2\left(B_0 - \dfrac{B_e}{2}\right) + \dfrac{4kT_e}{R_L}B_e \end{cases}$$

The error probability generated by using Gaussian optical signal model and threshold detection is given by:

$$P_e = \frac{1}{2}\,[P(0/1) + P(1/0)]$$

$$(16)\qquad \begin{cases} P(0/1) = \dfrac{1}{\sigma_1\sqrt{2\pi}}\displaystyle\int_{-\infty}^{s} \exp\left[-\frac{(i-\overline{i_1})^2}{2\sigma_1^2}\right] di = \frac{1}{2} erfc\left(\frac{\overline{i_1}-s}{\sigma_1\sqrt{2}}\right) \\ P(1/0) = \dfrac{1}{\sigma_0\sqrt{2\pi}}\displaystyle\int_{s}^{+\infty} \exp\left[-\frac{(i-\overline{i_0})^2}{2\sigma_0^2}\right] di = \frac{1}{2} erfc\left(\frac{s-\overline{i_0}}{\sigma_0\sqrt{2}}\right) \end{cases}$$

Knowing that and, where $erfc(x) = 1 - erf(x)$ and $erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x \exp(-t^2)dt$, where x is a real.

The resulting error probability expression is:

$$(17)\qquad \begin{cases} P_e(n) = \displaystyle\sum_{n=0}^{N-1} P_e\binom{N-1}{n} d^n(1-d)^{N-1-n} \quad \text{with} \quad d = \frac{\omega^2}{2L-\omega} \\ P_e(n) = \dfrac{1}{4}\left[erfc\left(\dfrac{\overline{i_1}-s}{\sigma_1}\right) + erfc\left(\dfrac{s-\overline{i_0}}{\sigma_0}\right)\right] \quad \text{with} \quad s = \dfrac{\sigma_0\overline{i_1} + \sigma_1\overline{i_0}}{\sigma_1+\sigma_0} \end{cases}$$

Equation (17) permits to obtain the error probability of an Optical CDMA communication system by taking into account the different parameters that characterize an optical channel and the number of users that can be multiplexed by a given code family.

This error probability is plotted in Figure 17 as a function of the optical power at the input of the optical amplifier. The simulation results shown in this figure demonstrate the validity of the analytical expression given by equation (17). The effect of the ratio B_o/B_e, which characterize the filtering conditions and determine the necessary bandwidth, is analyzed under amplifier gain condition G =30 dB.

It demonstrated that a BER lower than 10^{-4} is achieved for standard access, low power level and low cost filtering conditions (R_b= 155 Mbit/s P_l= – 54 dBm and B_o/B_e=100).

This value may be easily improved by using low cost Forward Correcting Codes (FEC), like Reed-Solomon FEC [20].

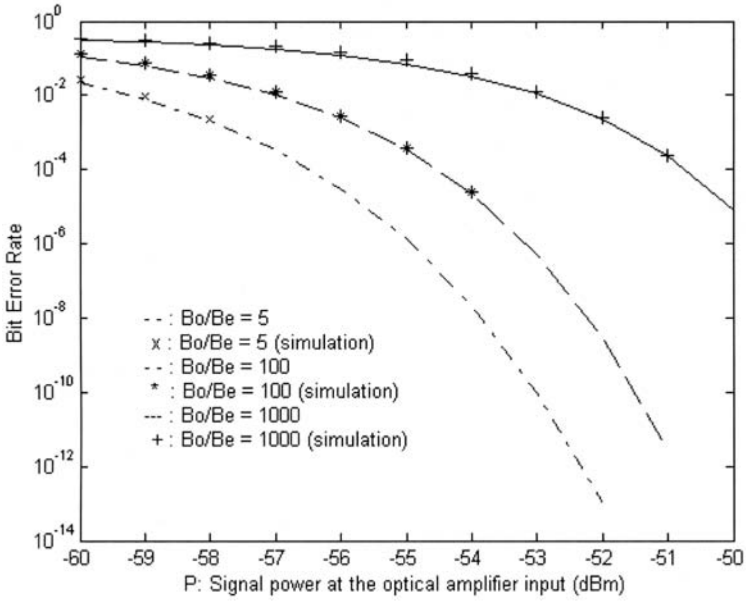

FIG. 17 – BER (Theory and Simulation) versus optical power at optical amplifier input. Optical amplifier gain G = 30 dB. Number of simultaneous user N = 5.

TEB (Théorie et Simulation) en fonction de la puissance optique à l'entrée de l'amplificateur. (Gain de l'amplificateur optique G = 30 dB, Nombre d'utilisateurs simultanés N= 5).

Remark: If we use an all-optical detection system, the photo-detection bandwidth is equivalent to the user data bit rate.

In Figure 18 the effect of multi access users on the BER is depicted. The graphs illustrate the relation between Multi-Access Interferences (MAI) and optical noises. MAI effects are limited by the noises introduced during the transmission via the optical channel and the upper bound of the associate error probability is limited by the error probability of the optical channel.

Indeed, the BER resulting from 29 simultaneous users is identical to the BER obtained for an equiprobable optical sequence, in the same physical condition, without using CDMA. So it is demonstrated that, in our optical model, the effects of MAI on the BER are conditioned and limited by the signal distortions generated by optical noises.

In Figure 19, threshold and multi-user detectors are compared. It is shown that multiuser detector present more interesting performances with lower constraints filtering conditions. Indeed, we associate to threshold detector a filter that has a wide of $B_o/B_e = 5$. With multi-user detector we use a low cost filter that has a wide $B_0/B_e = 100$. Under these conditions, for a power $P_1 = -55\,\text{dBm}$ at amplifier input, by using our multiuser detector, we improve the BER by 4 decades. In this case there is no need for resort to error correcting codes. This being, threshold detector permits to realize an all-optical CDMA system to work at higher rates than electro-optical systems.

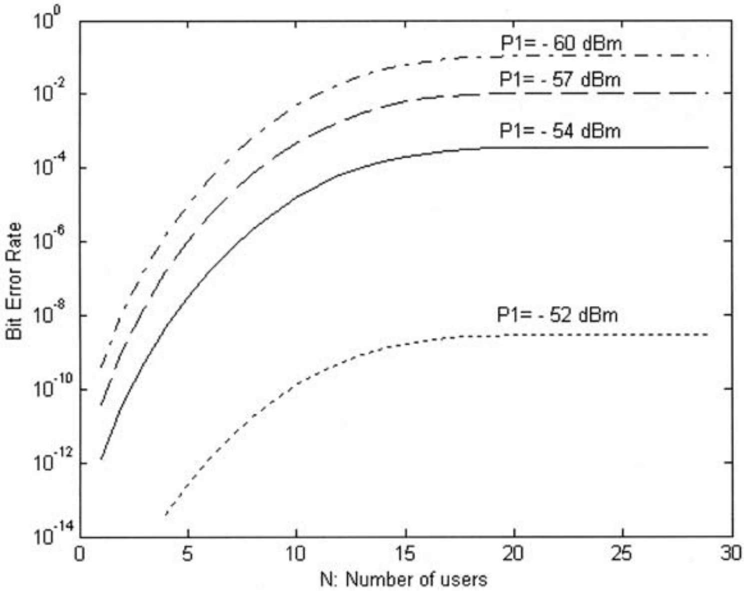

FIG. 18 – BER versus the number of simultaneous users. N = 29, L = 841, ω = 29.

TEB en fonction du nombre d'utilisateurs, N = 29, L = 841, ω = 29.

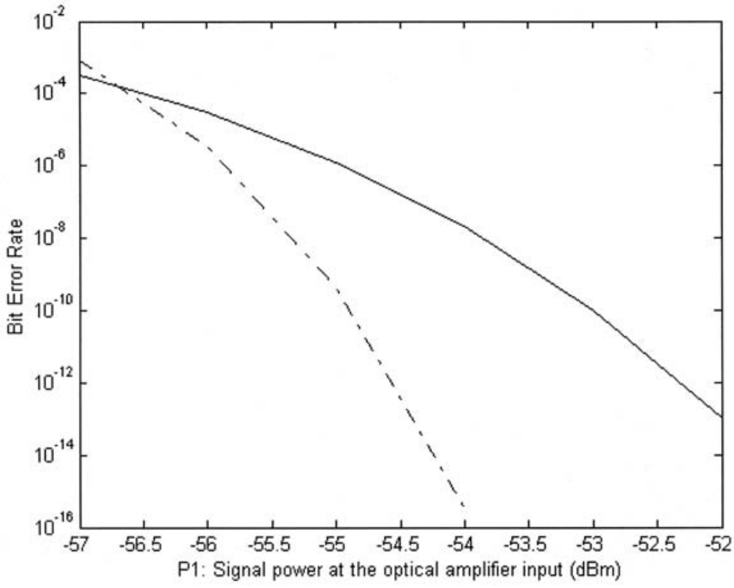

FIG. 19 – Comparison between threshold and multi-user detectors. G = 30 dBm and N = 5.

Comparaison entre la detection à seuil et la detection multi-utilisateur G = 30 dB and N = 5.

IX. CONCLUSION

Principal definitions of radio frequency CDMA have been recalled and this technique has been compared to other multi-access techniques, this to understand how CDMA operate in radio frequency field and may be adapted to the optical channel strains. These definitions point out the optical CDMA interest for optical transmissions.

Optical CDMA techniques have been presented including the specific domain of the optical channel. These constrains are partially relaxed by using appropriate optical code (OOC and PS). The optical generating algorithms were largely detailed and it is demonstrated that PS have a little advantages than OOC since PS codewords present the same or better multiplexing capacity with shorter sequences and the same auto and cross correlation proprieties.

Optical CDMA system has been investigated by using Gaussian model of the amplified optical channel. Indeed, this model take into account the most important noises introduced by amplification and detection, mainly signal to noise beating, noise-to-noise beating and thermal noise. In addition, different detection techniques were associated to our Optical CDMA system.

An analytic expression of the error probability, associated to a threshold detector is developed. This formulation includes the most important parameters of the optical channel, and arises the effect of filtering conditions by pointing out the benefit of a low optical to electrical bandwidth ratio on the resulting BER, this to bring closer the optical channel bandwidth and the user one. The simulations carried out thereafter confirm the theoretical expression of error probability. In the other hand, the model takes into account simultaneously MAI and optical noises generated by the optical channel. It demonstrates that the effect of MAI and optical codes, on the error probability, is directly related to optical noises introduced by the components of the optical channel.

At least, a comparison between multiuser and threshold detection is given and point out the advantage of multiuser detection methods since it obtained an improvement of the BER of *40 dB* under lower filtering constraints.

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