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# Blind Synchronization and Sequences Identification in CDMA Transmissions

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## ABSTRACT

*Blind sequences estimation methods, which work without prior knowledge about the transmitter, have been proposed in [1]–[3]; but they are restricted to a single-user context. Here, we extend the approach originally proposed in [2] to the multi-user context. We have developed a fast and efficient blind synchronization criterion based on the behavior of the FROBENIUS square norm of a submatrix that scans the intercepted signal correlation matrix. By using eigenanalysis techniques and theoretical linear algebra results, we prove that the maxima of this criterion correspond to the synchronization times with transmitters. Then, eigenanalysis techniques allow to estimate the spreading sequences. Eigenanalysis was associated with additional processing modules aimed at solving dephasing problems due to the transmission channel.*

*Key-Words : Spread spectrum communications, Blind multi-user detection, DS-SS CDMA, Spectrum surveillance, Blind synchronization, Blind estimation, Signal interception.*

## I. INTRODUCTION

Spread spectrum signals have been used in the military domain for a long time for secure communications [4]. Nowadays, their field of application includes civilian transmissions, especially CDMA ones [5]. Thanks to the properties of the pseudo-random sequences used, the CDMA technique allows one to solve the problem of the growing number of users within a frequency band. Moreover, these signals being often below the noise level (due to a very low signal-to-noise ratio (SNR)), there is nearly no chance to detect them even in a non-cooperative context, i.e. spectrum surveillance.

Several semi-blind approaches have been proposed in CDMA transmissions context [6]–[12]. They assumed that one or many transmitter parameters were known. This led us to propose a method to perform a blind

synchronization of the Direct Spread Spectrum Sequence Division Multiple Access (DS-SS CDMA) signal with the spreading sequences. Once blind synchronization has been performed, eigenanalysis techniques allow us to estimate the spreading sequences of the transmitters. Finally, by using these estimated sequences, the signal is demodulated and the transmitted symbols are estimated. In practice, the received signal is sampled and divided into temporal windows of duration equal to the symbol period which is estimated as described in [3]. Then, a blind synchronization is achieved through eigenanalysis techniques before estimating the spreading sequences.

This paper is organized as follows : Section II introduces the signal model and assumptions made. Section III describes the proposed synchronization method. Section IV deals with the sequences identification method. The synchronization method is derived in Section V to apply to the downlink transmission case. Section VI details and discusses the results of simulations. Finally, the conclusions are drawn in Section VII.

## II. DS-SS CDMA SIGNAL MODEL

In a DS-SS CDMA transmission, the symbols  $a_{n_k}$  are multiplied by a pseudo-random sequence to spread the bandwidth. The baseband signal at the receiver filter output can be written (see [13], [14]) as :

$$y(t) = \sum_{n=1}^{N_u} \sum_{k=-\infty}^{+\infty} a_{n_k} h_n(t - kT_s - \tau_n) + b(t)$$

$$\text{where } h_n(t) = \sum_{l=0}^{P-1} c_{n_l} p(t - lT_c)$$

The notations below are adopted

- $N_u$  is the total number of users,
- $a_{n_k}$  is the  $k^{\text{th}}$  symbol of the  $n^{\text{th}}$  user,
- $p(t)$  is the convolution of the transmission filter, channel filter (which represents the channel echoes) and receiver filter,

- $h_n(t)$  is a virtual filter corresponding to the convolution of all filters of the transmission chain with the spreading sequence  $\{c_{ni}\}_{i=0\dots P-1}$  for the  $n^{\text{th}}$  user, where  $P$  is the spreading sequence period,
- $T_s$  is the symbol period,
- $T_c$  is the chip period ( $T_c = T_s/P$ ),
- $b(t)$  is a centered white Gaussian noise of variance  $\sigma_b^2$  at the the receiver output,
- $\tau_n$  is the corresponding transmission delay for the  $n^{\text{th}}$  transmission path (thus for the  $n^{\text{th}}$  user) which satisfies the condition  $0 \leq \tau_n \leq T_s$  and remains constant during the observation time. It is assumed that  $\tau_1 \leq \tau_2 \leq \dots \leq \tau_n$ .

Let us assume that :

- The baseband symbols of variance  $\sigma_a^2$  are centered and uncorrelated.
- The noise is uncorrelated with the signal.
- $T_s$  is the estimated symbol period. All other parameters are unknown.
- The signals are received with the same power :  $\sigma_{s_i}^2 = \sigma_s^2 \forall i \in [1, N_u]$ , where  $s_i$  stands for the  $i^{\text{th}}$  signal ( $i^{\text{th}}$  user).
- The SNR (in  $dB$ ) at the the receiver filter output is negative (the signal is hidden in the noise).

### III. SYNCHRONIZATION CRITERION

The received signal is sampled and divided into  $N$  non-overlapping temporal windows of duration  $T_s$ . For clarity, we will detail the method only in the case of two users : we indeed, carried out theoretical developments later confirmed by simulations that enabled us to validate our method. So, in the following sections,  $N_u = 2$ ,  $\tau_1 = 0$ , and  $\tau_2 = \tau$ . The received signal is

$$y(t) = \sum_{k=-\infty}^{+\infty} (a_{1k} h_1(t - kT_s) + a_{2k} h_2(t - kT_s - \tau)) + b(t) \quad (1)$$

Let us note :

- $t = mT_s + t_0$ ,  $m \in \mathbb{N}^*$ ,  $0 \leq t_0 \leq T_s$ , where  $t_0$  is the desynchronization time between an entire symbol of the first signal and the analysis window,
- $t_1 = t_0 - \tau$ ,  $0 \leq t_1 \leq T_s$ , the desynchronization time between an entire symbol of the second signal and the analysis window.

The correlation matrix is given by :

$$\mathbf{R} = E \{ \mathbf{y}_l \mathbf{y}_l^H \} \quad (2)$$

where  $\mathbf{y}_l$  is a column vector containing the set of  $M$  samples in the  $l^{\text{th}}$  analysis window and  $E \{ . \}$  is the estimated mean over  $N$  analysis windows. Let us define the vectors  $\mathbf{h}_{i_0}$  and  $\mathbf{h}_{i_{-1}}$ ,  $i = 1, \dots, N_u$  :

- For the spreading waveforms  $h_1(t)$  and  $h_2(t)$ ,  $\mathbf{h}_{i_0}$  contains the end (durations  $T_s - t_0$ ,  $i = 1$  and  $T_s - t_1$ ,  $i = 2$ ) followed by zeroes (respectively durations  $t_0$  and  $t_1$ ).
- For the spreading waveforms  $h_1(t)$  and  $h_2(t)$ ,  $\mathbf{h}_{i_{-1}}$  contains zeros (durations  $t_0$ ,  $i = 1$  and  $t_1$ ,  $i = 2$ ) followed by the beginning (respectively durations  $T_s - t_0$  and  $T_s - t_1$ ).

Then, the intercepted signal in an analysis window can be written as :

$$\mathbf{y}_l = a_{1l} \mathbf{h}_{1_0} + a_{1_{l+1}} \mathbf{h}_{1_{-1}} + a_{2l} \mathbf{h}_{2_0} + a_{2_{l+1}} \mathbf{h}_{2_{-1}} + \mathbf{b} \quad (3)$$

where  $\mathbf{b}$  is the noise vector. The major problem with the multi-user case is the need to perform a blind synchronization. It consists in estimating the shifts  $t_0$  and  $t_1$  in order to readjust the analysis window on a entire symbol for either signal. Once this stage correctly carried out, each analysis window then contains either entire spreading sequence, apart from the effects of the global transmission filter. Let us assume  $\mathbf{h}_i(t)$  is null except on  $[0, T_s]$ . The signal is sampled at the period  $T_e$ , with  $T_s = MT_e$ ; the energy of each user is given by :

$$\epsilon_{h_i} = \epsilon_h = T_e \sum_{n=1}^M |\mathbf{h}_i(n)|^2 \simeq T_e \|\mathbf{h}_i\|^2, i = 1, 2 \quad (4)$$

Moreover, let us suppose that  $\epsilon_h$  is uniformly distributed over a symbol period; we obtain (5) and (6), which are both statistically valid if the length of the sequences is large enough, which is the current case [15], [16].

$$\begin{cases} \|\mathbf{h}_{1_0}\|^2 \simeq \left( \frac{T_s - t_0}{T_s} \right) \|\mathbf{h}_1\|^2 \\ \|\mathbf{h}_{1_{-1}}\|^2 \simeq \frac{t_0}{T_s} \|\mathbf{h}_1\|^2 \end{cases} \quad (5)$$

$$\begin{cases} \|\mathbf{h}_{2_0}\|^2 \simeq \left( \frac{T_s - t_1}{T_s} \right) \|\mathbf{h}_2\|^2 \\ \|\mathbf{h}_{2_{-1}}\|^2 \simeq \frac{t_1}{T_s} \|\mathbf{h}_2\|^2 \end{cases} \quad (6)$$

With respect to the unknown parameters  $t_0$ ,  $t_1$  and sampling period  $T_e$ , the correlation matrix can be expressed as :

$$\mathbf{R} = \sigma_a^2 \frac{\epsilon_h}{T_e} \left\{ \left( \frac{T_s - t_0}{T_s} \right) \mathbf{v}_{1_0} \mathbf{v}_{1_0}^* + \frac{t_0}{T_s} \mathbf{v}_{1_{-1}} \mathbf{v}_{1_{-1}}^* + \left( \frac{T_s - t_1}{T_s} \right) \mathbf{v}_{2_0} \mathbf{v}_{2_0}^* + \frac{t_1}{T_s} \mathbf{v}_{2_{-1}} \mathbf{v}_{2_{-1}}^* \right\} + \sigma_b^2 \mathbf{I} \quad (7)$$

where  $\mathbf{v}_{i_0}$  and  $\mathbf{v}_{i_{-1}}$  are normalized vectors of  $\mathbf{h}_{i_0}$  and  $\mathbf{h}_{i_{-1}}$ ;  $\mathbf{I}$  is the identity matrix. Since  $\sigma_s^2 = \frac{\sigma_a^2 \epsilon_h}{T_s}$ , let us note  $\rho = \frac{\sigma_s^2}{\sigma_b^2}$  the SNR of each spreading signal taken separately. The estimated correlation matrix is given by :

$$\mathbf{R} = \sigma_b^2 \left\{ \rho \beta \left\{ (1 - \alpha_0) \mathbf{v}_{1_0} \mathbf{v}_{1_0}^* + \alpha_0 \mathbf{v}_{1_{-1}} \mathbf{v}_{1_{-1}}^* + (1 - \alpha_1) \mathbf{v}_{2_0} \mathbf{v}_{2_0}^* + \alpha_1 \mathbf{v}_{2_{-1}} \mathbf{v}_{2_{-1}}^* \right\} + \mathbf{I} \right\} \quad (8)$$

where  $\beta = \frac{T_s}{T_e}$ ,  $\alpha_0 = \frac{t_0}{T_e}$  and  $\alpha_1 = \frac{t_1}{T_e}$ . Moreover, two different cases can occur according to the values of  $\alpha_0$  :

$$\begin{cases} \text{case 1 : } & \alpha_0 = \alpha_1 + u, \quad \text{for } 0 \leq \alpha_1 < 1 - u \\ \text{case 2 : } & \alpha_0 = u - (1 - \alpha_1) \quad \text{for } 1 - u \leq \alpha_1 < 1 \end{cases} \quad (9)$$

Fig. 1 illustrates one among the possible configurations.

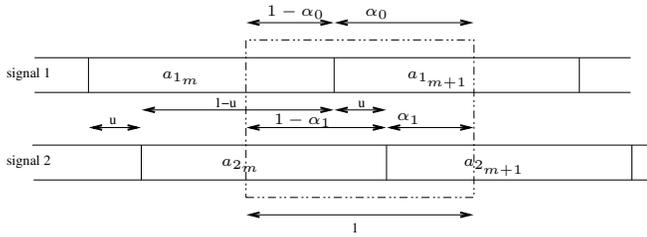


Fig. 1. Configuration : case 1

Equation (8) shows that the signal contribution is composed of four independent parts that generate four dominant eigenvalues. The proposed method consists in successively maximizing one of the two highest eigenvalues. In the event of synchronization of one of the users, Fig. 1 evidences the three remains independent parts, and thus three dominant eigenvalues. In CDMA systems, the intercorrelation between sequences is very low. According to (8), the eigenvalues are :

$$\begin{cases} \lambda_1 = \sigma_b^2 \{ \rho \beta (1 - \alpha_0) + 1 \} \\ \lambda_2 = \sigma_b^2 \{ \rho \beta \alpha_0 + 1 \} \\ \lambda_3 = \sigma_b^2 \{ \rho \beta (1 - \alpha_1) + 1 \} \\ \lambda_4 = \sigma_b^2 \{ \rho \beta \alpha_1 + 1 \} \\ \lambda_i = \sigma_b^2, \quad i = 5, \dots, N \end{cases} \quad (10)$$

Equation (10) demonstrates that, within a multiplicative factor, the sum of the eigenvalues is equal to the

total power (signal + noise). Thus, it is independent of the synchronization times ( $t_0$  or  $t_1$ ).

$$\sum_{i=1}^N \lambda_i = \sigma_b^2 \{ 2(\rho \beta + 1) + N \} \quad (11)$$

So, we have a set of values of constant sum (with a concentration on certain values) in the case of synchronization. The suitable criterion to highlight the phenomenon of concentration is the sum of squares. The developed method maximizes the FROBENIUS square norm of the estimated correlation matrix and avoids the calculation of the eigenvalues since the sum of their squares is equal to the sum of the correlation matrix elements. The FROBENIUS square norm of matrix  $\mathbf{R}$  ( $\|\mathbf{R}\|^2 = \sum_{i=1}^N \lambda_i^2$ ) is then written as :

$$\|\mathbf{R}\|^2 = \sigma_b^4 \{ 2\rho^2 \beta^2 [1 - \alpha_0 - \alpha_1 + \alpha_0^2 + \alpha_1^2] + 4\rho \beta + N \} \quad (12)$$

The problem can be simplified by focusing on the variable part of the criterion (12) noted  $F$ .  $\|\mathbf{R}\|^2$  and  $F$  have an alike behavior, it ensues that the results got for  $F$  will be valid for  $\|\mathbf{R}\|^2$  :

$$F = 1 - \alpha_0 + \alpha_0^2 - \alpha_1 + \alpha_1^2 \quad (13)$$

This relation does not emphasize that the term  $|\alpha_0 - \alpha_1|$  is constant. According to (10), we have :

$$\begin{cases} \text{case 1 : } & |\alpha_0 - \alpha_1| = \alpha_0 - \alpha_1 = u, \\ \text{case 2 : } & |\alpha_0 - \alpha_1| = \alpha_1 - \alpha_0 = 1 - u \end{cases} \quad (14)$$

#### A. Study of the case 1

In this case (see Fig. 1)

$$F = (1 - u + u^2) + 2(u - 1)\alpha_1 + 2\alpha_1^2 \quad (15)$$

The derivative of  $F$  is

$$\frac{dF}{d\alpha_1} = 4\alpha_1 + 2(u - 1) \quad (16)$$

It is canceled for  $\alpha_1 = \frac{1-u}{2}$ . Since  $0 \leq u < 1$ , the derivative is negative before this value and positive afterwards. It follows that the maxima of  $F$  are at the interval ends (cf. Fig. 2), i.e. for  $\alpha_1 = 0$ , and  $\alpha_1 = 1 - u$ , which is equivalent to  $\alpha_0 = 0$ .

#### B. Study of the case 2

In the second case ( $\alpha_0 = u - (1 - \alpha_1)$ ,  $1 - u \leq \alpha_1 < 1$ ), Fig. 3 can help for a better understanding. In a general way, the second case occurs, for fixed  $u$ , when  $\alpha_0 \leq \alpha_1$ ; in this case,  $\alpha_1 = (1 + \alpha_0) - u$ .

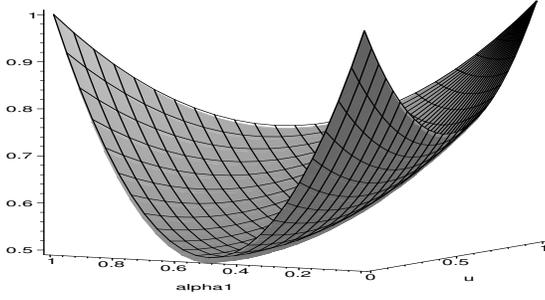


Fig. 2. Theoretical criterion (case 1)

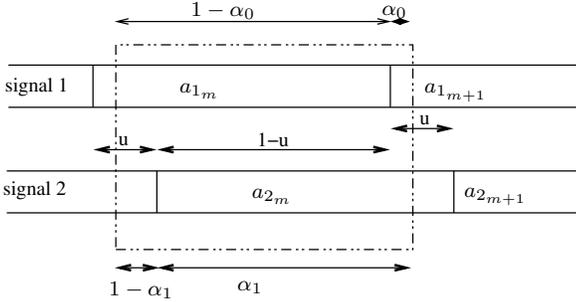


Fig. 3. Configuration : case 2

The criterion becomes :

$$F = (1 - 3u + u^2) + 2\alpha_1(u - 2) + 2\alpha_1^2 \quad (17)$$

The study of maxima of  $F$  in the second case leads to the same conclusions. The criterion derivative is canceled for  $\alpha_1 = 1 - \frac{u}{2}$ . Therefore, finally, the criterion presents two maxima, they correspond to synchronization with either spreading sequence, i.e.  $t_0 = 0$  or  $t_1 = 0$ .

#### IV. SEQUENCES ESTIMATION

After synchronization of one of the users ( $\alpha_1 = 0$  for example), the correlation matrix becomes :

$$\mathbf{R} = \sigma_b^2 \left\{ \rho\beta \left\{ \left(1 - \frac{t_0}{T_s}\right) \mathbf{v}_{1_0} \mathbf{v}_{1_0}^* + \frac{t_0}{T_s} \mathbf{v}_{1_{-1}} \mathbf{v}_{1_{-1}}^* + \mathbf{v}_2 \mathbf{v}_2^* \right\} + \mathbf{I} \right\} \quad (18)$$

where  $\mathbf{v}_2$  is the vector containing an entire symbol, i.e. the sequence previously used to spread out this signal (apart from the effects of the total transmission filter). Relation (18) then highlights three dominating eigenvalues, the others being equal to the power noise.

$$\begin{cases} \lambda_1 = \sigma_b^2 \{\rho\beta + 1\} \\ \lambda_2 = \sigma_b^2 \{\rho\beta(1 - \alpha_0) + 1\} \\ \lambda_3 = \sigma_b^2 \{\rho\beta\alpha_0 + 1\} \\ \lambda_i = \sigma_b^2, \quad i = 4, \dots, N \end{cases} \quad (19)$$

The largest eigenvalue corresponds to the eigenvector  $\mathbf{v}_2$ , i.e. the spreading sequence of the second signal; the two other dominant values correspond to the eigenvectors  $\mathbf{v}_{1_0}$  and  $\mathbf{v}_{1_{-1}}$  of the first signal.

The eigenvectors are calculated within a complex multiplicative factor due to diagonalization. The complex factor effects are canceled by normalizing the estimated eigenvector phase. It is made by maximizing its real part and imposing the positivity of its first component real part. In order to determine whether the sequence was initially complex or real, the variances of its real and imaginary parts after normalization are compared. The sequence is real when the ratio of the standard deviation of its real part-to-the standard deviation of its imaginary part exceeds 2.5. This threshold seems to be sufficient because of eigenvectors normalization. This stage allows us to eliminate the effects of the global transmission filter.

The last stage is the *binarization*. It consists in determining the chip period  $T_c$  (hence the length of the sequences) before seeking the binary sequence the nearest to the spreading sequence estimated in the least squares sense for each sequence to be estimated. The second step is the other eigenvector synchronization, i.e.  $\alpha_0 = 0$ .

#### V. DOWNLINK TRANSMISSIONS

The downlink transmissions case is obtained by assuming  $u = 0$ , i.e.  $\alpha_0 = \alpha_1$ , in all the previous equations. It can be viewed as a transmission with delay times equal or null for all users. The correlation matrix becomes :

$$\mathbf{R} = \sigma_b^2 \left\{ \rho\beta \left\{ (1 - \alpha_0) (\mathbf{v}_{1_0} \mathbf{v}_{1_0}^* + \mathbf{v}_{2_0} \mathbf{v}_{2_0}^*) + \alpha_0 (\mathbf{v}_{1_{-1}} \mathbf{v}_{1_{-1}}^* + \mathbf{v}_{2_{-1}} \mathbf{v}_{2_{-1}}^*) \right\} + \mathbf{I} \right\} \quad (20)$$

The FROBENIUS square norm is given by :

$$\|\mathbf{R}\|^2 = 4\sigma_b^2 \{2\rho(\alpha_0^2 - \beta\alpha_0 + \beta^2) + 4\rho\beta + N\} \quad (21)$$

The synchronization criterion becomes :

$$F = \alpha_0^2 - \beta\alpha_0 + \beta^2 \quad (22)$$

its derivative is canceled for  $\alpha_0 = \frac{\beta}{2}$ . With the adopted notations, this is equivalent to  $t_0 = \frac{T_s}{2}$ . The derivative is negative before this value and positive afterwards. It ensues that the maxima of  $F$  are at the ends, i.e. in  $t_0 = 0$ , and in  $t_0 = T_s$ , what is equivalent to  $t_0 = 0$ . After synchronization, the correlation matrix can be expressed as :

$$\mathbf{R} = \sigma_b^2 \left\{ \rho\beta \left\{ \mathbf{v}_1 \mathbf{v}_1^* + \mathbf{v}_2 \mathbf{v}_2^* \right\} + \mathbf{I} \right\} \quad (23)$$

Contrary to the asynchronous case, the two largest eigenvalues of the same matrix correspond to the two eigenvectors ( $\mathbf{v}_1$  and  $\mathbf{v}_2$ ). Each of them contains a pseudo-random sequences.

In most of the cases (for both downlink and uplink transmissions), and especially when the pseudo-random sequences used are very close, each estimated constellation can be a linear combination of the constellation obtained with each sequence. It is worth noting that this linear combination can be removed by using the method introduced in Appendix A and based on linear algebra theories. It allows one to retrieve the transmitted symbols.

### VI. SIMULATION RESULTS

Simulations were carried out with two real GOLD sequences, traditionally used in CDMA systems [14]. Their length was  $P = 2^n - 1 = 31$  ( $n = 5$ ). The chip frequency was  $F_c = 40$  Mhz, the initial sampling frequency was  $F_e = 200$  Mhz, the SNR was  $-3dB$  at the transmitter input. The initial number of window was  $N = 58$ , with a duration of  $550\mu s$ , and the number of samples was 32768. The symbols belong to a *QPSK* constellation. The two signals were respectively spread by the pseudo-random sequence  $n^{\circ}1$  and  $n^{\circ}2$  (Fig. 4) and lasted  $163.84\mu s$ . The estimated symbol period was  $T_s = 0.775\mu s$ . It was set  $t_0 = 0.1103$ ,  $t_1 = 0.4690$ , and then  $\tau = 0.3587$ .

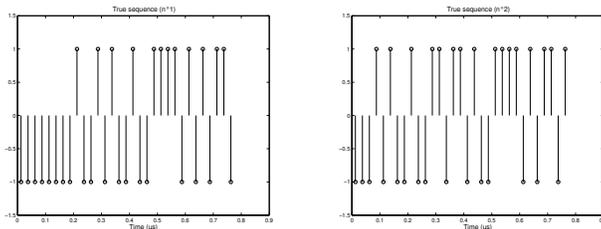


Fig. 4. True sequences

Fig. 5 shows the correlation matrix and evidences the overlapping of the two 2-dimension subspaces (left side on Fig. 5), which together generate four dominating eigenvalues (right side on Fig. 5), the others are equal to the additive noise variance. The correlation matrix was computed to highlight desynchronization times (between the two signals, and between each of them and the analysis windows). The diagonal of the correlation matrix shows them clearly.

Fig. 6 depicts the synchronization criterion calculated by moving along the diagonal of the correlation matrix

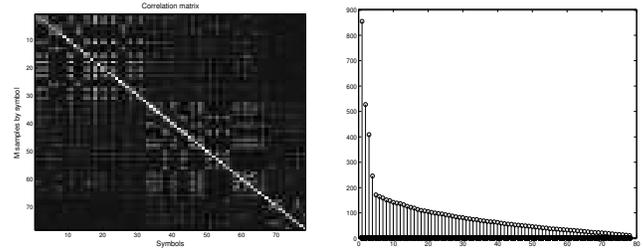


Fig. 5. Eigenanalysis before synchronization

and calculating the square norm of the shift-induced submatrix for each value of shift. This square norm will be maximum for the two clear zones to the deduction of desynchronization times. In agreement with the theory, there are two peaks of the criterion corresponding to the two maxima whose X-coordinates give times of desynchronization. The number of peaks give the number of active users over the analysis window.

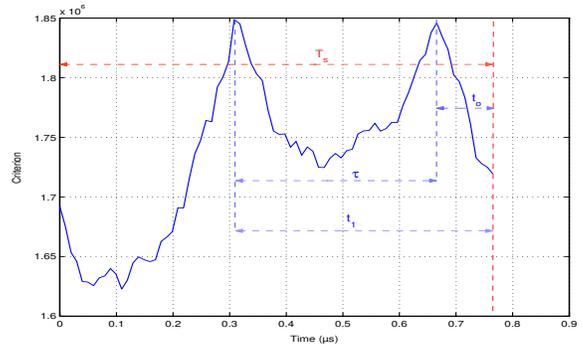


Fig. 6. Synchronisation Criterion

Fig. 6 gives :  $\hat{t}_0 = 0.1093$ ,  $\hat{t}_1 = 0.4670$ ; and the time delay  $\hat{\tau} = 0.3577$ . These values are very close to the true ones. The signal can now be synchronized. This stage can be interpreted as the extraction of two submatrices corresponding to synchronized signals (Fig. 7). In agreement with the theory, an eigenanalysis on one of them clearly shows three dominating eigenvalues (Fig. 7). The eigenvector corresponding to the largest eigenvalue contains one of the spreading sequences. The estimated value  $\hat{t}_1$  allows the other signal

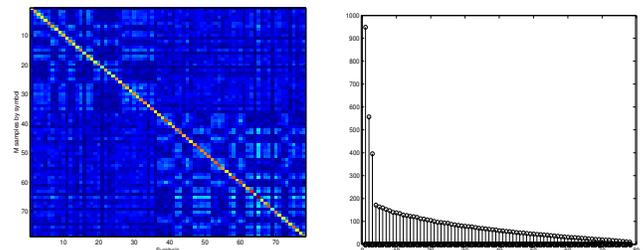


Fig. 7. Eigenanalysis after synchronization

synchronization. At this stage, we have an estimation of the pseudo-random sequences.

The estimated sequences are rectified to compensate for the channel-produced dephasing. The effects of global transmission filter are canceled by normalizing in phase. The values of spreading sequences being either  $+1$  or  $-1$ , among these bipolar sequences we need to find those that are the closest to the estimated sequences within the meaning least squares. Fig. 8 shows the two estimated bipolar sequences.

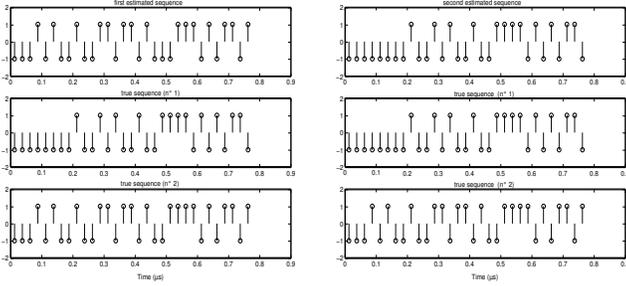


Fig. 8. Estimated sequences

Finally, the demodulation of estimated symbols, in cooperative or non cooperative contexts, needs an additional treatment. An example of constellations obtained after demodulation of the two signals is represented on Fig. 9; it is similar to those ( $QPSK$  modulation) obtained in cooperative context. Impact dispersions on constellations are due to the low SNR ( $-8.5dB$  at the receiver output).

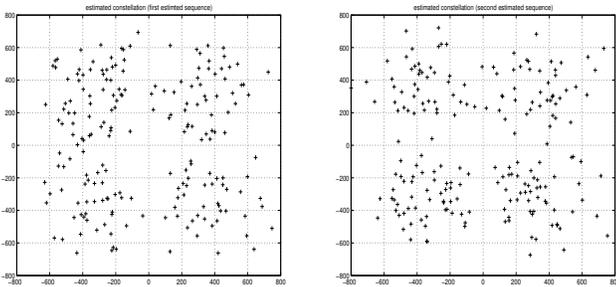


Fig. 9. Estimated constellations

## VII. CONCLUSION

We proposed, here, a new blind criterion for synchronizing and estimating spreading sequences in CDMA transmissions. We have focused on the synchronization criterion which is the most important step in our method. Moreover, in practice the proposed method requires no eigenvalues computing. Indeed,

one needs to compute only the sum of the estimated correlation matrix elements. Furthermore, the proposed synchronization criterion can provide a good estimation of the total number of users in the CDMA uplink transmissions.

Once estimated by the proposed method, pseudo-random sequences can be used in traditional CDMA multi-user receivers so as to recover the symbols. The additional processing modules used here aimed at solving dephasing problems due to the transmission channel.

The effects due to the number of analysis windows, SNR, the numbers of users and the selection of spreading sequences (i.e according to their correlation properties and their length) are still under study. This will enable us later to give the limits and performances of our method.

## APPENDIX

### A. Method for canceling the linear combination

Let us note  $\mathbf{V}$  a  $(q \times 2)$ -matrix whose columns contain the two estimated sequences;  $\mathbf{Y}$  is the corresponding  $(q \times N)$ -matrix (arrangement columns after columns), and  $\mathbf{Z} = \mathbf{V}^T \mathbf{Y}$  the matrix that contains the estimated symbols. Let us take a  $(2 \times 2)$ -unitary matrix  $\mathbf{A}$ , in the following form (without loss of generality) :

$$\mathbf{A} = \begin{pmatrix} \gamma & -\delta e^{j\theta} \\ \delta & -\gamma e^{j\theta} \end{pmatrix} \quad (24)$$

where  $0 \leq \gamma \leq 1$ , and  $\delta = \sqrt{1 - \gamma^2}$ . We define the following criterion :

$$C = \overline{(|z_1|^2 \cdot |z_2|^2)} - \overline{|z_1|^2} \cdot \overline{|z_2|^2} \quad (25)$$

where  $z_1$  and  $z_2$  respectively represent the first and second lines of matrix  $\mathbf{Z}$ ;  $\overline{(\cdot)}$  represents the average of  $(\cdot)$ . Then, we proceed by iteration on the possible values of  $\gamma$ . For each value, we compute the matrix  $\mathbf{A}$  and a new matrix :  $\hat{\mathbf{Z}} = \mathbf{Z}^T \cdot \mathbf{A}$ .

Among the values of  $\gamma$ ,  $\delta$  and  $\theta$ , we keep those that minimize the criterion  $C$ . Hence, the corresponding obtained matrix  $\hat{\mathbf{Z}}$  contains the estimated constellation. The results obtained with this method are illustrated below.

Fig. 10 shows the  $C$  criterion obtained in the downlink case, under the same experimental conditions as in

section VI. The values that minimize this criterion are approximatively :  $\hat{\gamma} = 0.8182$  and  $\hat{\theta} = 0.1468$ . Fig. 11

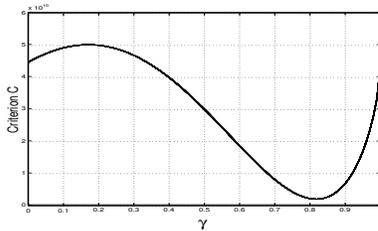


Fig. 10. Criterion C

represents the estimated constellation before and after treatment. It highlights (figure on left side) superimposed constellations, due to the linear combination. Once the linear combination has been removed, the final constellation obtained is very close to a QPSK constellation. The dispersion is due to the low SNR.

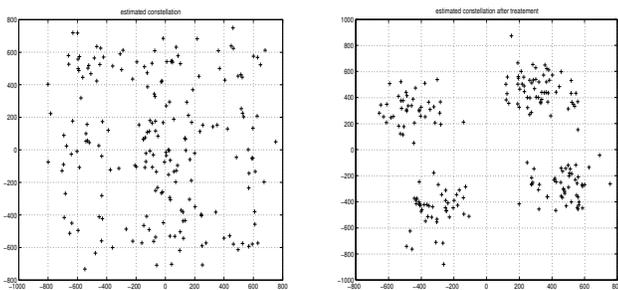


Fig. 11. Constellation before and after treatment

### B. Estimation of sequence and chip periods

The sequence bipolarization stage is held as follows : The minima  $L_{min}$  and maxima  $L_{max}$  for the length  $L$  of the estimated sequence are set. Then, each value of  $L$  is iterated to determine the bipolar sequence corresponding to the estimated sequence within the meaning of least squares. The value of  $L$  that gives the best auto-correlation property with the lowest mean square error is kept. Knowing the estimated symbol period  $T_s$  allows one to deduce the chip period. Hence, we compute the chip period :  $T_c = T_s/L$ .

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