Blind Demodulation for DS-CDMA transmission over frequency selective channels

Vincent Le Nir, Toon van Waterschoot, Jonathan Duplicy, and Marc Moonen

I. Abstract

In this paper, we focus our attention on blind demodulation for DS-CDMA transmission in the context of radio surveillance and military applications. We present a blind demodulation technique for DS-CDMA transmission over frequency selective channels. The technique exploits the autocorrelation properties of the transmitted signal to estimate the parameters (symbol duration, timing offset, phase offset, spreading sequences) and to demodulate the transmitted symbols without requiring any additional pilots. Simulation results are performed on various channel models with timing offsets.

II. Introduction

Direct sequence code division multiple access (DS-CDMA) has been employed in many standards such as IS-95, CDMA2000, WLAN 802.11, and 3G UMTS/WCDMA to increase the number of users, the speed of applications, the robustness to multipath channels and the difficulty for interception. In this paper, we describe a technique to blindly demodulate digital communications systems employing DS-CDMA. The technique exploits the autocorrelation properties of the transmitted signal to estimate the parameters (symbol duration, timing offset, phase offset, spreading sequences) and to demodulate the transmitted symbols without requiring any additional pilots.

The modulation chain of a DS-CDMA transmitter is represented on Fig. 1 and consists of:

- Channel coding and interleaving at a rate $1/T_s$
- Mapping to a BPSK or QPSK modulation (This operation can also be done after spreading and scrambling as they are linear operations)
- Spreading operation with spreading codes of length L at a rate $1/T_c$ (T_c is the chip duration) with the following relation $T_s = T_c L$. Usually the spreading codes are Walsh Hadamard sequences with variable length (UMTS) and are used to initiate multiple physical channels with the same user). Walsh Hadamard sequences have zero crosscorrelation and do not have good autocorrelation properties.
- Scrambling operation which consists of multiplying the spreaded data with a pseudo-random sequence at the chip rate $1/T_c$. Usually Gold codes are chosen for a downlink transmission and Kasami codes for an uplink transmission. Gold codes have good crosscorrelation and autocorrelation properties. A single Gold or Kasami code is given to each user/base station. In the following, we use the autocorrelation feature to detect the presence of DS-CDMA users in the spectrum.
- Pulse shaping using a Raised Cosine which consists of transmitting the data in a particular band without affecting non-licensed bands

V. Le Nir, T. van Waterschoot and M. Moonen are with the Department of Electrical Engineering (ESAT), Katholieke Universiteit Leuven, Belgium e-mail: vincent.lenir@esat.kuleuven.be

J. Duplicy is with Agilent Technologies, Rotselaar, Belgium

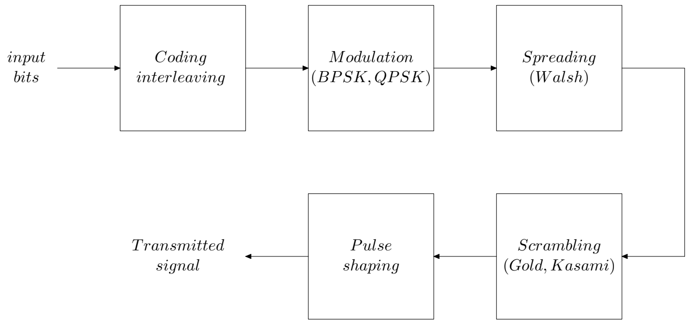


Fig. 1. Modulation chain of a DS-CDMA transmitter

To blindly estimate the symbol duration of a single DS-CDMA user, [1] has proposed to use the fluctuations of the autocorrelation feature exploiting the properties of the Gold codes. This work has been extended to multi-user and multi-rate scenarios in a downlink or uplink transmission where the users are synchronous or asynchronous [2]. The fluctuations of the autocorrelation feature allows to estimate the symbol duration of the different DS-CDMA users which are present in the spectrum. In this paper, we present another technique to estimate the symbol duration using the normalized second order moment of the squared magnitude of the autocorrelation function, and we extend the work of [1], [2] to frequency selective channels using realisitc channel models.

The paper is organized as follows. In section II, we present the DS-CDMA signal model and we review the estimation techniques for the symbol period T_s [1], [2]. Then, we present the new technique for symbol duration estimation and the procedure to blindly demodulate the DS-CDMA signals with timing offset and spreading sequence estimation. In section III, simulation results are presented with realistic channels models. Finally, conclusions are drawn in section IV.

III. Description of the algorithm

The non-data-aided technique presented in this paper has been developed in the context of radio surveillance and cognitive radio systems for DS-CDMA transmission. The wideband received signal may contain multiple signals of interest. Therefore, the received signal is sampled in a large bandwidth to include existing and future DS-CDMA standards. The carrier frequencies, bandwidths, and average powers of the detected signals are estimated using the power spectrum or the cyclic spectrum. After downconversion to baseband and low-pass filtering, each signal of interest is processed through a feature detection block to determine whether or not it is an DS-CDMA signal based on its symbol duration T_s detection. If a DS-CDMA signal is detected, we can recover the transmitted symbols by estimating the timing offset, phase offset and the spreading sequences. Each signal of interest can be modeled as a received sequence $\mathbf{y} = [y(0) \dots y(N-1)]^T$ of length N such that:

$$y(i) = e^{j(2\pi\epsilon i+\phi)} \sum_{l=\theta}^{L-1+\theta} h(l-\theta)x(i-l) + n(i) \quad i \in [0 \dots N-1] \tag{1}$$

where $\mathbf{x} = [x(0) \dots x(N-1)]^T$ is the transmitted signal vector oversampled by the ratio between the cut-off frequency of the low-pass filter and the transmitter maximum frequency, the $h(l)$'s are the oversampled multipath channel coefficients with L the number of channel taps, $\mathbf{n} = [n(0) \dots n(N-1)]^T$ is the vector of Additive White Gaussian Noise (AWGN), ϕ the receiver phase offset, ϵ the receiver frequency offset and θ the receiver timing offset.

A. *Estimation of the symbol duration for a single DS-CDMA user*

For a single DS-CDMA user, [1], [2] have proposed to use the autocorrelation feature on the scrambling codes (Gold codes) to determine the symbol duration T_s. The autocorrelation feature is appropriate to determine the symbol duration T_s of a DS-CDMA signal owing to the good autocorrelation properties of the Gold codes. In the case of infinite code length, one can see the correlation of the transmitted signal variations on Fig. 2.

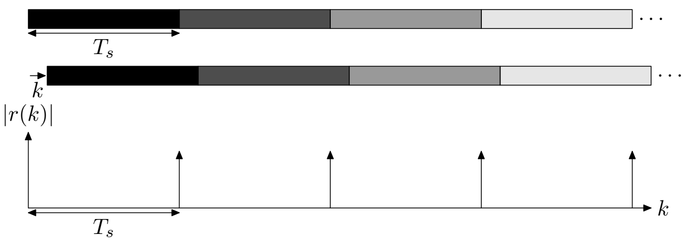


Fig. 2. Correlation on a DS-CDMA signal

The estimation of the symbol duration T_s uses correlation properties of the received sequence. The correlation of the received sequence can be written as:

$$r(k) = \frac{1}{N} \sum_{i=0}^{N-1} y(i)y^*(i-k) \quad k \in [0 \dots N-1] \tag{2}$$

with k the shift index. [1], [2] proposed to divide the sequence of length N into M blocks of size T, and then adding the contribution of each block. Then the feature used is not based on the correlation itself but on the fluctuations of this correlation. For each block of length T, the correlation becomes:

$$r_m(k) = \sum_{i=0}^{T-1} y(mT_s+i)y^*(mT_s+i-k) \quad k \in [0 \dots T-1] \tag{3}$$

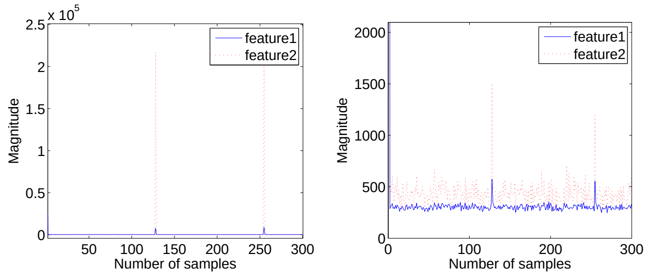
Then a second order moment (variance) measures the fluctuations of the correlation function:

$$\mathbf{\Phi}_{r_m(k)} = E[|r_m(k)|^2] = \frac{1}{M} \sum_{m=0}^{M-1} |r_m(k)|^2 \quad k \in [0 \dots T-1] \tag{4}$$

However, one can see that the feature [1], [2] assume an average $E[r(k)] = 0$ for the second order moment. In the following instead of taking the second order moment of the correlation function (this feature will be called feature1), we take the normalized second order moment of the square magnitude of the correlation function (referred to as feature2). This leads to:

$$\begin{aligned} \mathbf{\Phi}_{|r_m(k)|^2} &= E[(|r_m(k)|^2 - \mu_m(k))^2] \\ &= \frac{1}{M^2} \sum_{m=0}^{M-1} (|r_m(k)|^2 - \mu_m(k))^2 \qquad k \in [0 \dots T-1] \end{aligned} \tag{5}$$

Fig. 3 shows an example with a Gold sequence of length 127 at SNR=0 dB and SNR=-10 dB. We take a transmission of 1000 symbols giving 127000 data symbols. The length blocks are chosen to be $T = 300$, providing $M = 211$ blocks. One can see that the symbol duration can be well approximated by the difference between two peaks even at low SNR. Moreover, feature2 leads to a better performance compared to feature1 at moderate SNR (SNR=0 dB) as the ratio between the lowest peak and highest noise level is larger in the case of feature2 than feature1.

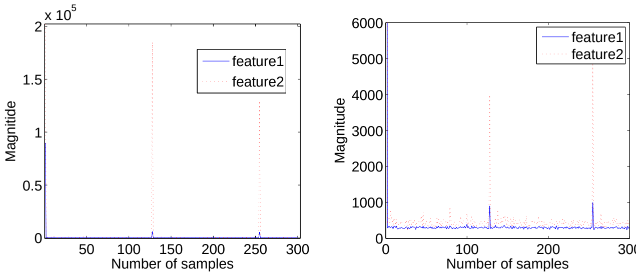


(a) SNR=0 dB (b) SNR=-10 dB

Fig. 3. Comparison of different features for the estimation of the symbol duration for a single DS-CDMA user

B. *Estimation of the symbol duration for multiple synchronous or asynchrounous DS-CDMA users*

In this case it is necessary to distinguish between a downlink transmission where the different users contains the data of all the other users. The user of interest retrieve its data through its own Gold or Kasami code. In an uplink transmission, some delay are introduced between the different users as they transmit asynchronously. However, we see in the following simulations that these parameters have no incidence on the detection algorithm. Fig. 4 shows an example with 4 users having the same data rates (and therefore the same symbol period) either in an uplink asynchronous transmission or in a downlink synchronous transmission using Gold sequences of length 127 at SNR=0 dB and SNR=-10 dB. We take a transmission of 1000 symbols giving 127000 data symbols. The length blocks are chosen to be $T = 300$, providing $M = 211$ blocks. As the Gold sequences are orthogonal between each other, the peak of the fluctuations of the correlation feature sum each other at the delay corresponding to the symbol duration. Therefore the symbol duration can be better approximated in the multi-user case than the single user case if the users have the same data rates.



(a) SNR=0 dB (b) SNR=-10 dB

Fig. 4. Comparison of different features for the estimation of the symbol duration for a 4 DS-CDMA users

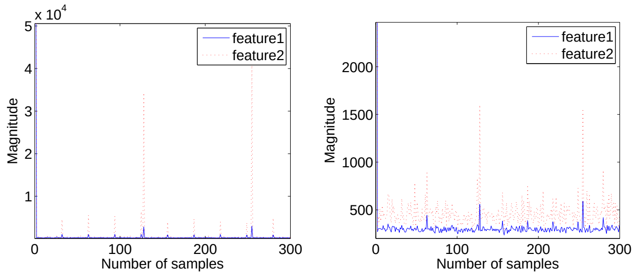
C. Estimation of different symbol durations for multiple synchronous or asynchrounous DS-CDMA users

We saw in the previous paragraph that asynchronous or synchronous DS-CDMA users having the same data rates (also the same symbol duration) allows a better estimation of the symbol duration for that particular set of users. However, it is known that in DS-CDMA, different users can have several data rates (and therefore several symbol duration). Therefore it is necessary to see if the correlation feature can detect multiple symbol durations.

Fig. 5 shows an example with 2 groups of 2 users having the different data rates (and therefore the same symbol period) either in an uplink asynchronous transmission or in a downlink synchronous transmission at SNR=0 dB and SNR=-10 dB. The first group of 2 users use 2 Gold sequences of length 127. The second group of 2 users use 2 Gold sequences of length 31. We take a transmission of 930 symbols for the first group and 3810 symbols for the second group giving 118110 data symbols. The length blocks are chosen to be $T = 300$, providing $M = 196$ blocks. One can see that the highest peaks corresponds to the group of users having the longest Gold codes. Smaller peaks occur at a dealy multiple of the second group of Gold codes. Therefore it is still possible to determine the different symbol duration but a higher SNR is necessary than for the multi-user case with similar data rates.

D. Synchronization

After the estimation of the symbol duration T_s which can be done by finding the multiplicity factor between multiple



(a) SNR=0 dB (b) SNR=-10 dB

Fig. 5. Comparison of different features for the estimation of the symbol duration for a 4 DS-CDMA users

autocorrelation peaks, one has to find the timing offset to perform the synchronization. The synchronization criteria is based on the maximization of the frobenius norm for the average correlation matrix [2] and can be written as:

$$\theta_{opt} = \underset{\theta}{\operatorname{argmax}} || \sum_{m=0}^{M-1} \mathbf{R}_{\theta,m} ||^2 \tag{6}$$

with

$$\mathbf{R}_{\theta,m} = \mathbf{y}_{\theta,m} \mathbf{y}_{\theta,m}^H \tag{7}$$

and

$$\mathbf{y}_{\theta,m} = [y(mT_s + \theta), \ldots, y((m+1)T_s + \theta - 1)]^T \tag{8}$$

After timing offset correction, the spreading sequence corresponds to the eigenvector of the largest eigenvalue for the average correlation matrix

$$\sum_{m=0}^{M-1} \mathbf{R}_{\theta_{opt},m} = \mathbf{V} \mathbf{\Lambda} \mathbf{V}^H \tag{9}$$

with $\mathbf{\Lambda} = diag(\lambda_0, \ldots, \lambda_{T_s-1})$ the eigenvalue matrix and $\mathbf{V}$ the unitary matrix whose columns contain the eigenvectors of the corresponding eigenvalues. Then, we perform a phase offset estimation based on modulation stripping [3], [4]. The principle of modulation stripping is to calculate the rotated angle of the received constellation. For a QPSK constellation, the angle of the fourth order moment is calculated taking into account several blocks and then divided by four. Hence, the modulation stripping for a QPSK constellation can be applied to determine the phase offset of an estimated complex spreading sequence. Similarly, the modulation stripping for a BPSK constellation can be applied to determine the phase offset of an estimated real spreading sequence. The modulation stripping formula for QPSK is given by:

$$\phi_k = arg \left(\frac{1}{T_s} \sum_{i=0}^{T_s-1} v_{i,0}^4 \right) \tag{10}$$

with $v_{i,0}$ the matrix element at row i and column 0. After phase offset correction, one can perform a binarization of the estimated spreading sequence, followed by the despreading and modulation stripping on the estimated symbols to completely demodulate the received signal [2].

IV. Simulation results

In this section, we evaluate the performance of the presented techniques for DS-CDMA with 10 MHz bandwidth on Stanford University Interim (SUI) [5] channel models with various time and frequency offsets. Simulations results are performed on 100 Monte Carlo trials from 10 to 30 DS-CDMA symbols. Two types of channels are chosen, the SUI-1 channel which have LOS components for flat terrain with light tree density and the SUI-4 channel which has NLOS components for hilly terrain with heavy tree density. The different characteristics of SUI channels models are given in Table I.

SUI 1 channel			
	Tap 1	Tap 2	Tap 3
Delay (μs)	0	0.4	0.9
Power (dB)	0	-15	-20
K factor	4	0	0
Doppler (Hz)	0.4	0.3	0.5
SUI 4 channel			
	Tap 1	Tap 2	Tap 3
Delay (μs)	0	1.5	4
Power (dB)	0	-4	-8
K factor	0	0	0
Doppler (Hz)	0.2	0.15	0.25

TABLE I
SUI CHANNEL MODELS

Fig. 6 shows the performance comparison between the two features in terms of probability of correct detection P_d (which indicates that the algorithm correctly estimates the symbol duration T_s) versus SNR on SUI-1&4 channel models from 10 to 30 recorded DS-CDMA symbols. From this figure, we can conclude that the features are rather insensitive to the channel (as good for SUI-4 as for SUI-1). Moreover, feature1 shows better performance results than feature2 when 10 DS-CDMA symbols are used for the estimation. The gap between the two features reduces as the number of recorded DS-CDMA symbols increases from 10 to 30. Using feature1, at -3 dB we are sure to correctly estimate the symbol duration T_s using a record of 10 DS-CDMA symbols on generic SUI channel models.

Fig. 7 shows the performance of the synchronization algorithm (maximization of the frobenius norm of the average correlation matrix) in terms of probability of correct detection P_d (which indicates that the algorithm correctly estimates the timing offset θ_{true}) versus SNR on SUI-1&4 channel models using 30 recorded DS-CDMA symbols taking into account the previous estimation of the symbol duration T_s feature1. The algorithm performs better for the SUI-1 channel as the most predominant channel path is the first arrival path while for the SUI-4 channels the most predominant channel path is usually not the first arrival path. Finally, to estimate the spreading sequences and to retrieve the transmitted symbols, one can follow the procedure [2].

V. Conclusion

In this paper, we have focused our attention on blind demodulation for DS-CDMA transmission in the context of radio surveillance and military applications. We have presented a blind demodulation technique for DS-CDMA transmission over frequency selective channels which exploits the autocorrelation properties of the transmitted signal to estimate the parameters (symbol duration, timing offset, phase offset, spreading sequence) and to demodulate the transmitted symbols without requiring any additional pilots. Simulation results were performed on various channel models with timing and frequency offsets, showing good performance at low SNR for the estimation for the different parameters.

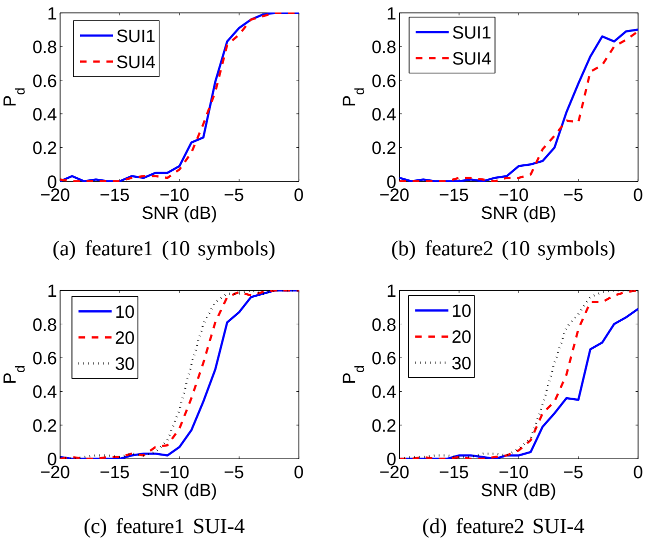


Fig. 6. Probability of correct detection of the symbol duration T_s versus SNR

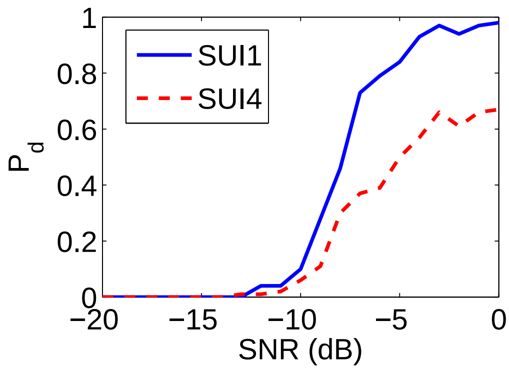


Fig. 7. Probability of correct detection of the timing offset θ versus SNR

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