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Multipath Combining in Chaotic Direct-Sequence Spread Spectrum Communications through Dual Estimation

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***Abstract*— The aim of the present paper is to increase the reliability of a Kalman filter-based DS-SS receiver by considering in the state space models the multipath coefficients and associated delays. The objective being to operate at very low SNRs in shallow water (to achieve furtive transmissions) and with the need of a limited computationnal cost, the implementation relies on the Unscented Kalman Filter, which is known to be more robust than the popular Extended Kalman Filter. The proposed receiver schemes are discussed and compared using experimental datas.**

I. Introduction

Over the past fifteen years, a great research effort has been devoted towards the development of efficient chaos-based modulation techniques. This motivation originates from theoretical results about the synchronizing capability of two identical chaotic systems that start from different initial conditions [1]. Due to its random-like behavior, chaos not only spreads the spectrum of the information signal, thus providing robustness against channel distorsions, but also acts as an encryption key. Hence, covertness of transmissions can be ensured and due to intricate dynamics of the signals, it is extremely difficult for the unauthorized user aware of the transmission to access the information. Other potential benefits have to be noticed, among others the sharing of channel resources via Code Division Multiple Access (CDMA), resulting from weak crosscorrelation of chaotic signals, and reduced complexity of transmission devices.

Numbering chaos-based modulation schemes have been investigated in the literature, such as chaotic direct-sequence or frequency-hopped spread spectrum techniques, chaotic masking, chaos-shift keying or chaotic time-hopping. For an overview of this research field the reader is referred to [2], [3]. By this time, most of the reported results deal with numerical simulations or analytical computations in case of a gaussian channel, considering eventually the multipath propagation. For the underwater channel, practical investigations seem to be almost unexistant; to the knowledge of the authors, only a paper of Atkins and Fenwick [4] investigates the pertinence of chaos-based underwater communications, owing to a OFDM scheme. The aperiodic nature of chaotic signals and their extreme dependance upon initial conditions bring new problems when designing a digital receiver, especially if it relies on the chaos synchronization property demonstrated by Pecora and Caroll.

Direct-Sequence Code Division Multiple Access (DS-CDMA) techniques become more and more popular in part due to the increasing number of wireless applications (telephony, positionning...). In case of underwater acoustics, DS-CDMA is a recommended technique for the development of shallow water networks [5]. In this context, Gold or Kasami codes are usually used as spreading codes. However, the well-known properties and construction rules of these popular codes may be used by the unintended user to intercept or even demodulate the transmitted signal, as reported in [7], [8]. The adoption of chaotic codes can limit this problem, provided that the degree of performance remains comparable with that of conventionnal approaches in terms of Bit Error Rate, number of users and implementation complexity.

In an earlier paper [9], the authors investigated the feasibility of Chaotic Direct-Sequence Spread Spectrum communications underwater though digital simulations, by computing the acoustic field using a ray method. It was shown that a receiver relying on the chaos synchronization property of Pecora and Caroll was viable for positive Signal-to-Noise-Ratios (SNRs). Despite the recent progress in designing chaos synchronization-based receivers [10], experiments at sea have shown that such an approach is not yet robust enough to ensure good performances in very noisy shallow water channels [11]. In this last paper, the authors investigate two receiver schemes with the objective of covert transmissions. The first one is the conventionnal correlator-based receiver (ignoring the multipath). The second receiver, operating at chip-rate in order to better track channel fluctuations, make use of a mixed parameter and state estimation (dual estimation) to find the symbol and residual carrier phase error. No chaos synchronization is achieved in this case; the original spreading code is employed once the receiver is symbol synchronized (the same Delay Locked Loop as that of the RAKE receiver is used).

The aim of the present paper is first to report the performances of this dual estimation-based receiver in very noisy shallow water, for a single user. It was shown in [11] that only one path was sufficient to succesfully demodulate. However, in cases where many paths exhibit similar amplitudes, it will be useful to take advantage of the multipath propagation to increase the robustness. Our second objective is then to generalize the previous dual estimation approach by consider-

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ing the mutipath terms. Due to the nonlinear nature of the estimation problem and in order to keep a good tradeoff between robustness and complexity, the dual estimator is implemented owing to Unscented Kalman Filters [13].

The paper is organized as follows. Section 2 summarizes the principle of a Chaotic DS-SS (CD3S) transmitter. Then, the dual estimation-based receiver is explained in section 3. Its basic version, relying on one path models, is first described; then a generalization is proposed in order to better exploit the multipath nature of the received signal. Finally, the pertinence of the proposed schemes is shown in section 4 through experimental datas.

II. The Chaotic DS-SS Transmitter

The general scheme of a CD3S transmitter is shown in figure 1. The information bits are first modulated, through DBPSK (Differential Binary Phase Shift Keying) in our case, to get the symbols b_k that are then spreaded using the chaotic code $c_k \in \mathbb{R}$ evolving at the chip rate $F_c \gg F_b$, where $F_b = 1/T_b$ is the symbol rate. At this point we make no assumption on the type of chaotic sequence, only that it is given by the recursive monodimensional equation $c_k = f(c_{k-1})$.

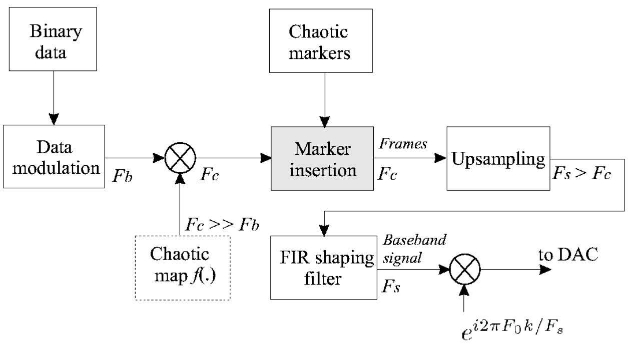

Fig. 1. Structure of the CD3S transmitter

The spread spectrum signal will then take the form $x_k = b_{\lfloor k/L \rfloor} c_k$, where $\lfloor \times \rfloor$ denotes the integer part of the enclosed number $\times$ and where $L = F_c/F_b$ stands for the processing gain. The choice of the processing gain depends upon the available channel bandwidth, the desired data rate and bit error rate together with the existence of any covertness constraint. In order to help the receiver to synchronize and also to initialize various estimators on the receiver side, few pilot symbols (having the same chaotic dynamics as that of the spreading code) are inserted. The signal is finally passed through a square root band limiting Nyquist filter and before the transmission through the communication channel, a sinusoidal carrier modulation is done.

III. A Dual Kalman Filtering-based Multipath Combining Receiver

A. Overview of the proposed receiver

The overall structure of the proposed dual estimation-based receiver is depicted in figure 2. Once the transmitted signal

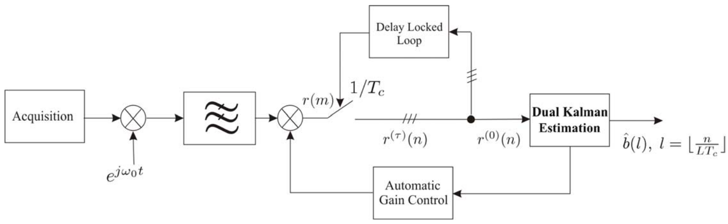

Fig. 2. Overview of the proposed CD3S receiver

has been acquired and brought back to baseband, the symbol timing has to be recovered prior to demodulation. This task is processed by a conventionnal Delay-Locked Loop (DLL) which uses as inputs three branches corresponding to the downsampled reference signal (denoted by an index $\tau = 0$) and its early and late versions (denoted by indexes $\tau = -1$ and $\tau = +1$, respectively) :

$$r^{(\tau)}(n) = r\left(m + \tau T_s + n\frac{T_c}{T_s}\right) \qquad (1)$$

The branch leading to the best cross-correlation with the original spreading code is then selected for demodulation through Kalman filtering. Thanks to this approach the symbol and residual carrier phase error will be tracked at chip rate simultaneously. Due to the nonlinearity of the phase observation model and the noisy conditions resulting from the objective of covert transmissions, an Unscented Kalman Filter (UKF) is chosen [13]. This filter is known to offer a better robustness than the popular Extended Kalman Filter, at a comparable computationnal complexity.

Two cases will be discussed : firstly, the filtering models will be derived taking into account only one useful path, even in presence of any significant multipath propagation; in this case the gain of the input signal is controlled prior to demodulation. The authors reported experimental performance of this aproach in a previous paper [11], in the case of high SNRs. Despite its apparent simplicity, it will be shown in the sequel that this method still performs well at low SNRs in multipath shallow water channels. In order to take advantage of the multipath nature of the incoming signal, a second approach will be proposed, generalizing the dual estimation-based receiver. In this case, the delays and associated gains of the selected paths are computed at the DLL level and the AGC loop is removed from Fig. 2.

B. Derivation of the Kalman filtering models

This subsection is devoted to the models used by the Dual Kalman Estimation block. A one-tap model, using one path only, is first described. Then a more general model, designed to exploit some of the multipath signal power, is proposed. In both cases, the Dual Kalman Estimator has the same parallel structure : one filter is devoted to symbol estimation at time step k, using as parameter last phase estimate $\hat{\phi}_{k-1}$ and a second filter tracks phase fluctuations using knowledge of last symbol $\hat{b}_{k-1}$. Due to the nonstationnary nature of underwater channels, the two filters operate at chip rate.

1) One tap model: This first solution relies on the following dynamic and observation models for estimating the symbol b_k:

$$\begin{cases} b_{k+1} = b_k + v_k^b \\ \mathbf{y}_k = b_k.f(c_{k-1}).\mathbf{g}\left(\hat{\phi}_{k-1}\right) + \mathbf{n}_k \end{cases} \quad (2)$$

where c_k is the spreading code used at the transmitter and where $v_k^b \sim \mathcal{N}\left(0, Q^b\right)$ is a noise term, necessary to let the filter track symbol changes.

The phase is filtered owing to a first order model :

$$\begin{cases} \phi_{k+1} = \phi_k + v_k^\phi \\ \mathbf{y}_k = sgn\left(\hat{b}_{k-1}\right).f(c_{k-1}).\mathbf{g}(\phi_k) + \mathbf{n}_k \end{cases} \quad (3)$$

Again, a noise $v_k^\phi \sim \mathcal{N}\left(0, Q^\phi\right)$ is introduced not only for tracking phase fluctuations but also for taking into account modelling errors. Higher order models could be used for filtering the phase but, as will be shown in the next section, the first order considered here achieves a good tradeoff between performances and computationnal complexity.

In the previous models, $\mathbf{g}(.)$ denotes a vector realizing a projection along the real and imaginary axes to get the observation $\mathbf{y}_k = \left[y_k^{Re}, y_k^{Im}\right]^T$:

$$\mathbf{g}(\phi_k) = \left[\begin{array}{cc} \cos(\phi_k) & \sin(\phi_k) \end{array}\right]^T \quad (4)$$

Both observation models make use of an additive noise term $\mathbf{n}_k = \left[n_k^1, n_k^2\right]^T$ to reflect the noisy measure. We have considered $\mathbf{n}_k \sim \mathcal{N}(\mathbf{0}, \mathbf{R})$, with the covariance matrix $\mathbf{R} = \frac{\sigma^2}{2}\mathbf{I}_2$ and σ^2 the considered variance of the gaussian noise supposed in the channel. We observed that with a considered observation noise variance in a relatively large interval the general performances of the system does not suffer great deviations. All the noises $\left\{v_k^b, v_k^\phi, \mathbf{n}_k\right\}$ are supposed independent between each other and with the other parameters that construct the model.

2) Multiple taps model: From the experimentations we have remarked that the general delays and phase differences between the propagation paths remain mostly constant and so we can write a generalized model considering the phase ϕ_k of the main path as reference and estimating the phase differences $\{\varepsilon_k^i\}_{i=1,\ldots,M+1}$ of some selected paths occuring at time delays $\{\triangle_i T_c\}$.

The dynamic and observation models giving the symbol estimates then becomes

$$\begin{cases} b_{k+1} = b_k + v_k^b \\ \mathbf{y}_k = b_k.\left(G_k^0 f(c_{k-1}).\mathbf{g}\left(\hat{\phi}_{k-1}\right) + \right. \\ \left. + \sum_{i=1}^M G_k^i f\left(c_{k-\triangle_i-1}\right).\mathbf{g}\left(\hat{\phi}_{k-1} + \hat{\varepsilon}_{k-1}^i\right)\right) + \mathbf{n}_k \end{cases} \quad (5)$$

where the set $\{G_k^i\}_{i=1,\ldots,M+1}$ stand for the gains of the selected paths, computed through cross-correlation at the DLL stage and where $\hat{\phi}_{k-1}$ denote last estimate of the reference phase, associated to the main path, and $\{\hat{\varepsilon}_{k-1}^i\}_{i=1,\ldots,M}$ being the differences between $\hat{\phi}_{k-1}$ and the phases of the other selected paths.

To track all the phase terms, a second Kalman filter is employed, relying on the models below:

$$\begin{cases} \begin{bmatrix} \phi_{k+1} \\ \varepsilon_{k+1}^1 \\ \vdots \\ \varepsilon_{k+1}^M \end{bmatrix} = \begin{bmatrix} \phi_k \\ \varepsilon_k^1 \\ \vdots \\ \varepsilon_k^M \end{bmatrix} + \mathbf{v}_k^\phi \\ \mathbf{y}_k = b_k.\left(G_k^0 f(c_{k-1}).\mathbf{g}(\phi_k) + \right. \\ \left. + \sum_{i=1}^M G_k^i f\left(c_{k-\triangle_i-1}\right).\mathbf{g}\left(\phi_k + \varepsilon_k^i\right)\right) + \mathbf{n}_k \end{cases} \quad (6)$$

where $\mathbf{g}(.)$ is the vectorial phase decomposition function considered above 4, and $\mathbf{y}_k$, $\mathbf{n}_k$ being the observation state and noise vector

$$\mathbf{y}_k = \left[y_k^{Re}, y_k^{Im}\right]^T, \mathbf{n}_k = \left[n_k^1, n_k^2\right]^T \quad (7)$$

The noises are again supposed zero mean gaussian distributed and independent with the other parameters that construct the model:

$$v_k^b \sim \mathcal{N}\left(0, Q^b\right) \ , \ \mathbf{v}_k^\phi \sim \mathcal{N}\left(0, \mathbf{Q}^\phi\right)$$

The particular phase estimation model considered above with a very small variation of phases between the paths will have an impact on the process covariance matrix $\mathbf{Q}^\phi$, with smaller values for the elements associated with the relative phase errors. For the observation noise $\mathbf{n}_k \sim \mathcal{N}(\mathbf{0}, \mathbf{R})$ will keep the same properties as in the case presented above.

One important problem posed by the model above is the estimation, prior to the model application, of the path gains G_k^i and the relative delays interval between the paths $\triangle_i$; At the moment this question is addressed through correlation computations, in a similar way as that used in a standard RAKE receiver.

IV. Experimental results

In a previous work [11] it was reported that the one-tap model has good performances regarding a BER criteria in case of high SNRs. So the objective was twofold: First, to analyse the behavior of this one-tap based receiver in a covert transmission context (SNR below 0 dB); and second, to evaluate if the introduction of the generalized models, that take advantage of multipath propagation, yield better performances.

An experiment at sea was conducted at the bay of Brest (France) in july '03 to evaluate the pertinence of these CD3S receivers. The acoustic channels encountered were all of shallow water type, with a depth going from 20 m to 40 m. For almost all the measured impulse responses in noisy conditions (SNRs between -10 dB and -5 dB at the receiver input), a very low number of paths was noticed. Considering two propagation paths was generally sufficient. This was the case for the signal with the estimated channel impulse response considered in figure 3. We have to mention the response was given by a Maximal Ratio Combining RAKE receiver which was also used to give relative performance evaluation.

The signal characteristics are: DBPSK modulation, $N_s = 200$ transmitted symbols, *logistic* spreading code at chip rate $F_c = 4410\,Hz$ with processing gain $L = F_c/F_b = 63$, carrier

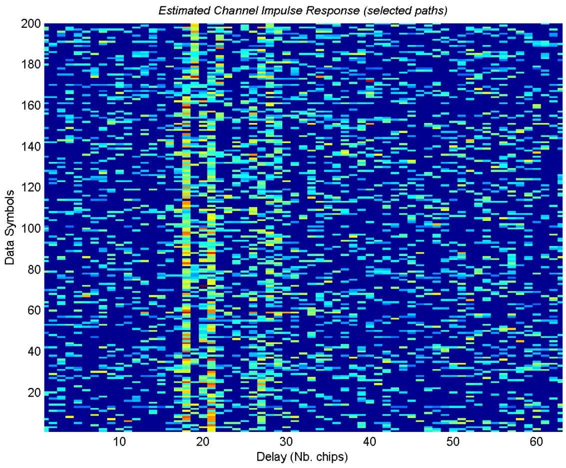

Fig. 3. Channel impulse response estimated with RAKE structure

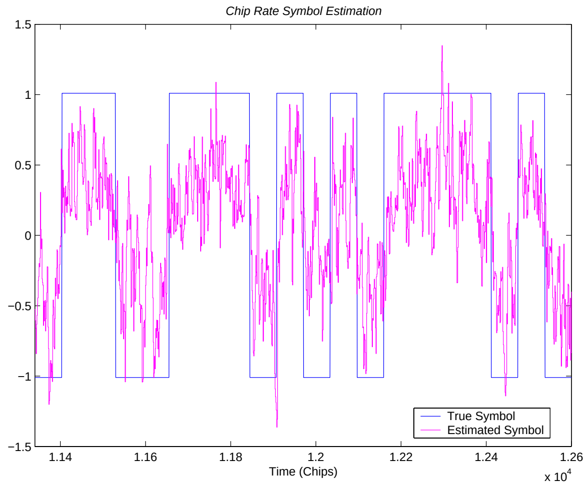

Fig. 4. Symbol estimation for one tap model

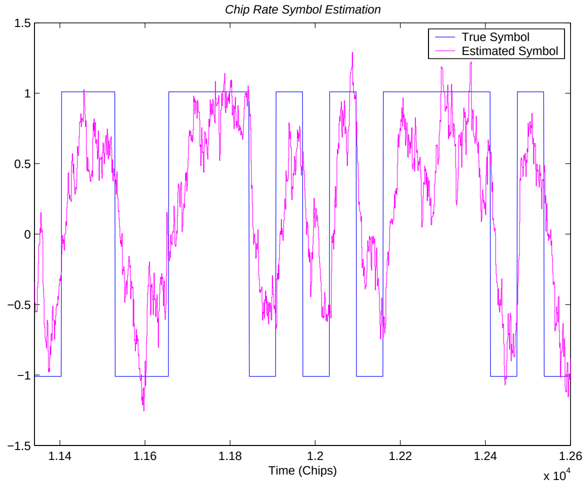

Fig. 5. Symbol estimation for two taps model

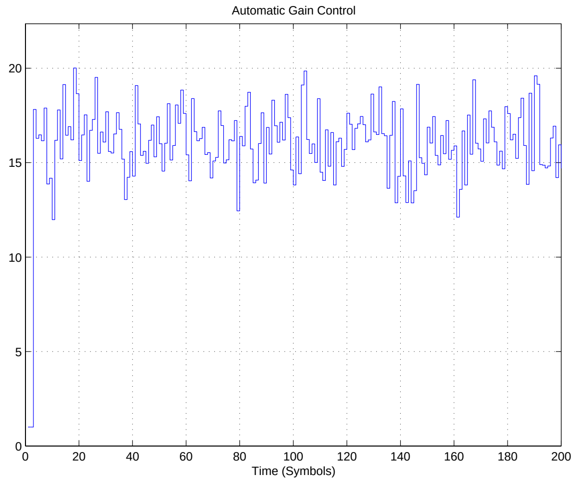

Fig. 6. Gain estimation for one tap model

frequency $F_0 = 8820Hz$ and an estimated CNR in the Nyquist band of about -8 dB.

From the channel impulse response we observe that only two of the propagating paths are energetic and so we will use a two tap model with separate gains and phases estimation.

The general approach that we will follow is to directly compare how the phases and symbol estimation have changed from one tap to the two taps model. In figures 4 and 5 we have considered the representation of the estimated last 20 symbols which can provide some insights over the qualitative manner of the symbol estimation. The selection of the last symbols also assures us that the filter has passed over some transition period.

From a qualitative point of view we observe a better estimation achieved by the two tap filter with a good distinction of the estimated symbol.

If we consider the gain estimation problem we pass from the statistical approach which was considered for the one tap model to the correlator based gain estimation considered for each of the paths in the case of the two tap model. Generally the statistical method offers a better estimate being less influenced by impulsive noise and higher phase variations, also to be observed from the dynamical range the gains have. Another comment associated to the figure 7 is the relatively equality between the energy on the selected paths.

If we consider now the phase estimation problem, excepting a small transition period, generally we have the same characteristic with a linear phase decrease. Taking into account also the figure 10 we can observe a small estimated relative phase error between the paths which grows with the time but tends to be asympthotic to a constant value. We associate this to the transition period necessary for the filter to converge towards the true state.

For the code delay diagram we have selected to represent the delays estimated for the two paths model. This estimation being independent of the models considered the characteristic evaluated for the first path in figure 11 will be identical for the one tap model. One important observation is that the relative delays between the two energetic paths considered is generally constant.

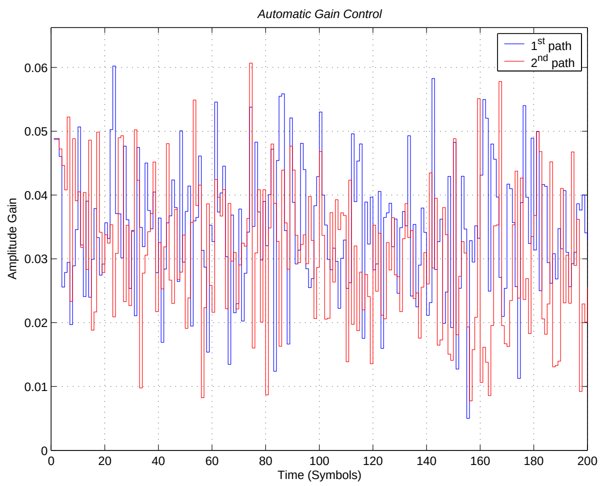

Fig. 7. Paths gain estimation for the two taps model

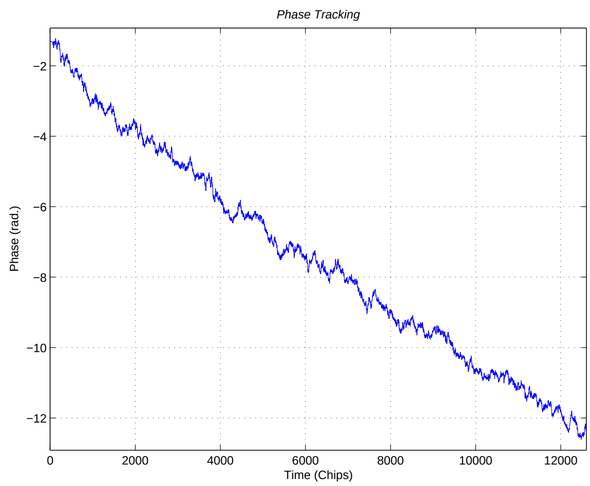

Fig. 8. Phase estimation for one tap model

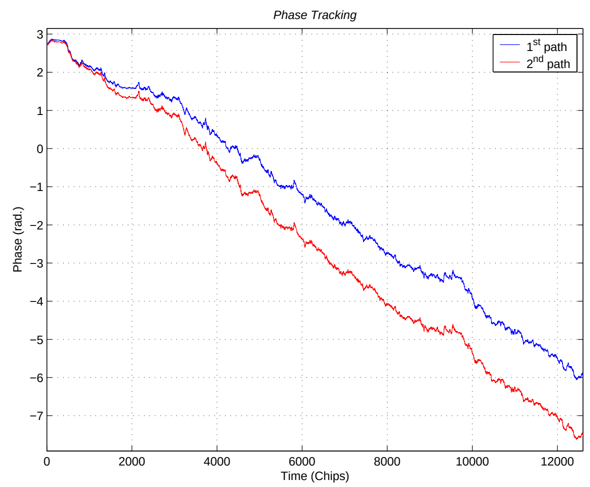

Fig. 9. Phase estimation for two taps model

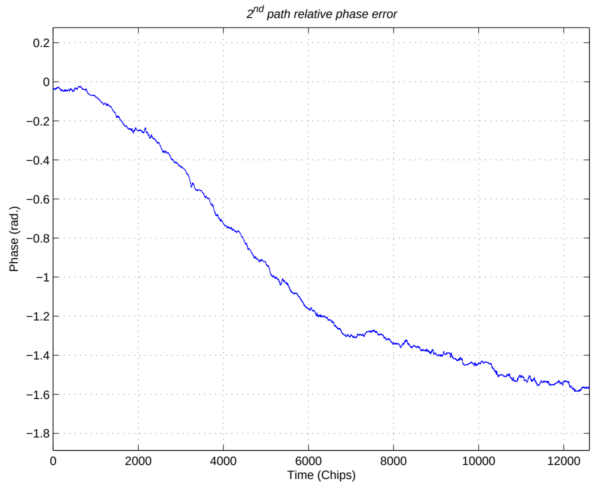

Fig. 10. Relative phase difference estimate

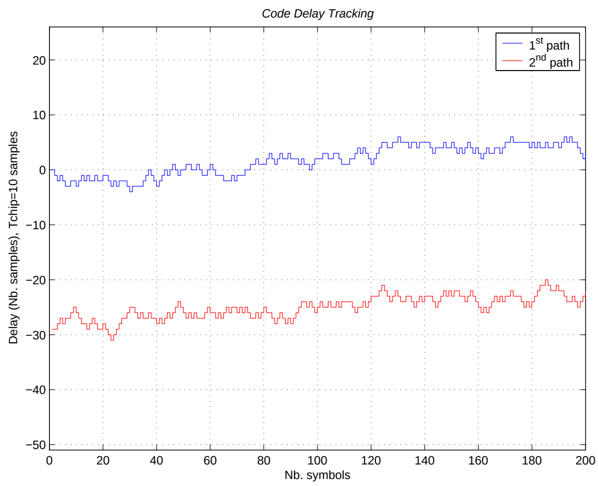

Fig. 11. The delay estimated by the DLL for the two taps model

From the performations point of view we have compared the two methods based on nonlinear filtering with the more classical MRC RAKE receiver for the given signal and we have observed no error for the information retrieved for either one tap and two taps model, with the RAKE receiver presenting one error over the 200 symbols transmitted.

V. Conclusions

The problem of covert digital transmissions has been considered in this paper. The objective in such a context being to avoid any spreading code periodicity (DS-SS scheme), a chaotic dynamical system is chosen as the spreading code generator. One solution to demodulate in noisy conditions is to achieve a RAKE combining at symbol rate with decision feedback (as no pilot symbol is available inside a data frame). In presence of rapid channel changes this receiver can lead to poor performances in case of large processing gains. Our objective was then to propose any potentially better solution, considering a chip rate processing. A dual estimation scheme has been proposed to address this question.

Due to the nonlinear nature of the estimation problem and the very noisy conditions, Unscented Kalman Filters are chosen to implement the receiver. Two variant are discussed : the first one considers only one path even in presence of many strong paths over the channel; the second is a generalization of the first approach to better exploit the multipath nature of the communication. These two receivers have been tested at sea for various conditions (processing gains, chip/central frequencies, SNRs...). Despite its simplicity, we noticed very good performances for the one-tap dual UKF-based receiver. In many situations, this receiver offers a BER comparable to that obtained via the multiple-tap solution. This last solution is more interesting in cases where many paths having almost equal powers exist.

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