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AUTOMATIC GAIN CONTROL IN A KALMAN FILTER BASED SYNCHRONIZATION CHAOTIC RECEIVER

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Abstract- **It has been recently pointed out than the Kalman filter is a powerful tool for the synchronization of chaos, which remains a major difficulty in the development of efficient chaos based digital communication systems, capable of operating over nonstationnary channels. The input signal power fluctuations, which often causes large errors in synchronizing chaotic waveforms, is discussed in this paper. The automatic gain control will be solved in two manners, the first one relying on a modification of the chaotic dynamics and the second one by matching the second order statistics of the original chaotic spreading code. The performance of these approaches will be illustrated through numerical simulations for a symmetric chaos shift keying system (i.e. chaotic direct sequence spread spectrum). A dual Unscented Kalman filtering scheme will be achieved at the receiver to demodulate and synchronize simultaneously.**

Index Terms: **chaos synchronization, gain control, Dual state estimation, Unscented Kalman filter**

I. INTRODUCTION

In the last few years, a great research effort has been devoted towards the development of efficient chaos-based modulation techniques [1] [2]. This motivation originates from theoretical results of Pecora and Caroll about the synchronizing capability of two identical chaotic systems that start from different initial conditions [3]. Due to its random-like deterministic behavior, chaos not only spreads the spectrum of the information signal but also acts as an encryption key. Hence, covertness of transmissions can be ensured and due to intricate dynamics of the received signals, it will be extremely difficult for the unauthorized user aware of the transmission to access the information.

To date, most of the results available in the litterature have been derived through numerical simulations (most often for the additive white gaussian noise channel) and few practical investigations have been reported. As remarked in [4], the property of a chaotic synchronization is attractive as it permits to greatly simplify if not totally remove the complex acquisition and tracking blocks that are present in any conventionnal spread spectrum communication system. But, as a consequence of the non periodic nature and the extreme sensitivity of chaos, it is not so easy to achieve the chaotic synchronization process in practical situations.

It has been recently proven [5] that Kalman filter synchronization methods (or more generally state space estimation techniques) can potentially outperform standard synchronization methods. Moreover, by including the transmitted information in the models, the demodulation and chaotic synchronization can be achieved in a simultaneous manner (dual estimation scheme). Obviously, the performances of such a receiver mainly rely on the choice of the adaptive filter. For an application on frequency selective nonstationnary channels, the use of Unscented Kalman filters (UKF, [6][7]) has been suggested in [8]. In presence of nonlinear dynamics, the UKF is known to be more accurate that the standard Extended Kalman Filter (EKF) with a comparable computational complexity and an easier implementation.

To get acceptable performances in practice, the input signal power fluctuations has to be compensated before any demodulation. The automatic gain control will be solved in two ways in this paper : The first approach is based on a modification of the chaotic dynamics that has been used by the transmitter; the second approach relies on a feedback control in order to match the second order statistics of the transmitted chaotic spreading code.

The paper is organized as follows. In Section II, we briefly present the structure of the communication system and an overview of synchronization process in a dual UKF receiver is given. The methods for gain control are then presented in the section III and the concluding remarks are given in section IV.

II. CHAOTIC DIRECT-SEQUENCE SPREAD SPECTRUM AND THE DUAL KALMAN FILTERING RECEIVER

Figure 1 shows the general scheme of a Chaotic Direct Sequence Spread Spectrum (CD3S) digital communication system, which is a special case of Chaos Shift Keying. The information bits are first modulated, usually through BPSK (Binary Phase Shift Keying), to get the symbols b_n. The spreading operation is then done by multiplication of the data symbols b_n, belonging to $\{-1, +1\}$ in case of BPSK, with a code c_k, evolving at a rate $F_c \gg F_b$, F_b being the data rate. The signal c_k belongs to the trajectory of a chaotic dynamical system f:

$$c_k = f(c_{k-1}) \tag{1}$$

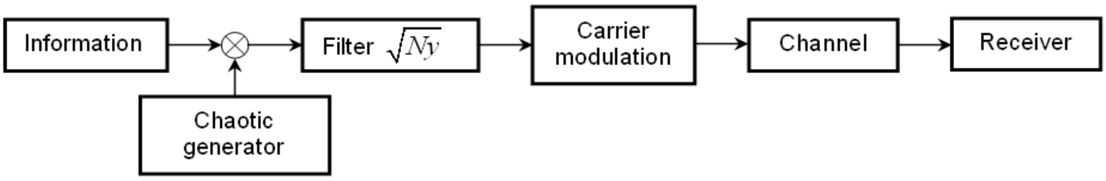

Fig. 1. General scheme of a chaotic DS-SS system

The spread spectrum signal is then given by :

$$x_k = b_{\lfloor k/L \rfloor} c_k \tag{2}$$

where $\lfloor \times \rfloor$ denotes the integer part of the enclosed number $\times$, and $L = F_c/F_b$ stands for the processing gain of the system. The choice of L results from a tradeoff between the available bandwidth of the channel, the desired data rate and bit error rate together with the existence of any covertness constraint.

The signal is then passed through a square root band limiting Nyquist filter and finally, before the transmission through the communication channel, a sinusoidal carrier modulation is done.

As suggested recently [9], the chaotic synchronization and the symbol detection can be achieved at the same time thanks to parallel Kalman filtering (dual estimation process). The general scheme of such a dual Kalman filter receiver is given in figure 2.

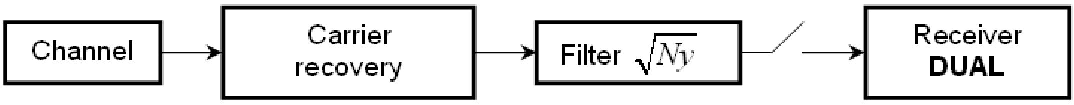

Fig. 2. General scheme of a DUAL receiver

In what follows, no complex values will be considered at the dual Kalman processing level. This means that a separate carrier recovery block (e.g. Costas Phase Locked Loop) is needed to compensate any carrier phase deviation.

As shown by figure 3, the dual Kalman filtering scheme enables the estimation of the original chaotic spreading code c_k together with the data symbol b_k at chip rate F_c from noisy observations y_k. Each of the two filters uses last estimate of the other as a parameter. The general model used is given by the equations (3), (4)

The dynamical model and the observation model used for code estimation take the following form:

$$\begin{cases} c_{k+1} = \mathrm{sgn}(\hat{b}_{k-1}) f(c_k) + v_k^c \\ y_k = \mathrm{sgn}(\hat{b}_{k-1}) c_k + n_k \end{cases} \tag{3}$$

where $f(\cdot)$ stands for the non-linear chaotic function, and where the gaussian noise sequence $v_k^c \sim \mathcal{N}\left(0, \mathcal{Q}^c\right)$, independent of the past and current state c_k, reflects the model uncertainty due to channel imperfections; the noise term $n_k \sim \mathcal{N}(\prime, \mathcal{R})$ in the observation model will be mainly dependent upon the Signal-to-Noise-Ratio (SNR) at the input of the receiver.

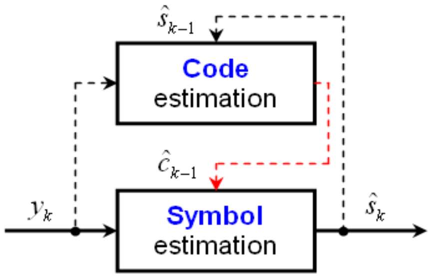

Fig. 3. DUAL estimator block

Similarly, the symbol will be estimated at chip rate through the following dynamical and observation models:

$$\begin{cases} b_{k+1} = b_k + v_k^b \\ y_k = b_k f(\hat{c}_{k-1}) + n_k \end{cases} \tag{4}$$

where the gaussian noise sequence $v_k^b \sim \mathcal{N}\left(\prime, \mathcal{Q}^{\lfloor}\right)$, independent of the past and current state b_k, will influence the adaptability of the symbol filter; a low value Q^b will result in slow changes whereas a larger value will result in rapid variations of the symbol estimates.

It must be emphasized that thanks to the set of noise terms $\{v_k^c,\ v_k^b,\ n_k\}$ this dual Kalman receiver can still operate on frequency selective channels, whereas the multipath propagation is not explicitely taken into account in Eqs (3) & (4).

Now, we can focus on the automatic gain control problem, which greatly influence the global performances of chaos based digital receivers; The logistic map will be considered as the chaotic generator, due to its favorable correlation properties :

$$c_k = 1 - 2c_{k-1}^2 \tag{5}$$

III. THE GAIN CONTROL METHODS

For an application over realistic channels, an efficient power control method is required to avoid a severe degradation of the chaotic synchronization perfromances. Even for a stationary channel with a non unitary gain large synchronization errors can occur, with a rapid degradation of the synchronization performances.

To achieve the gain control we have multiple options; The first one, generally used in practice, is the use of a control loop independent of the received signal characteristics before the receiver itself, but it will ensure only a limited gain control, that can still greatly influence the receiver performances, and that can also behave badly at some noise levels. So we propose two methods of gain control who are working in parallel with the receiver itself.

The **first method** is considering a modification on the system model, transferring the channel gain variation to the informational signal. In case of a BPSK modulation, this non-unitary deviation of the binary data will not influence the detection process. Moreover this modality of gain control can be considered for any type of phase modulation.

The original map is modified to get a novel chaotic function $\tilde{f}$ defined as:

$$\tilde{f}(x_k) = \begin{cases} f(x_k), |x_k| \leq 1 \\ -1, |x_k| \leq 1 \end{cases} \tag{6}$$

and then, the demodulation (through dual Kalman filtering scheme for example) will be processed according to new models, instead of (3) & (4) :

$$\begin{cases} c_{k+1} = \hat{b}_{k-1}\tilde{f}(c_k) + v_k^c \\ y_k = \hat{b}_{k-1}c_k + n_k \end{cases} \tag{7}$$

$$\begin{cases} x_{k+1} = b_{k+1} = b_k + v_k^b \\ y_k = b_k\tilde{f}(\hat{c}_{k-1}) + n_k \end{cases} \tag{8}$$

As shown by figure 4 the modification of the chaotic dynamics at the receiver level consists in a simple limitation of the dynamic range of the incoming signal, thus transferring ideally the channel gain fluctuations to the information signal. This property is illustrated by figure 5 a), where it is noted that the dynamic range of the estimated informational signal varies in phase with the transfer gain of the channel.

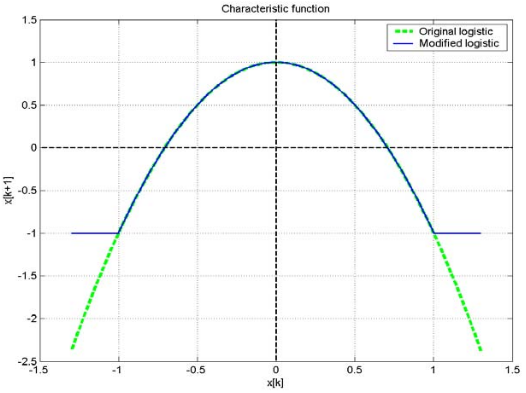

Fig. 4. Modified and original characteristic function for the logistic map

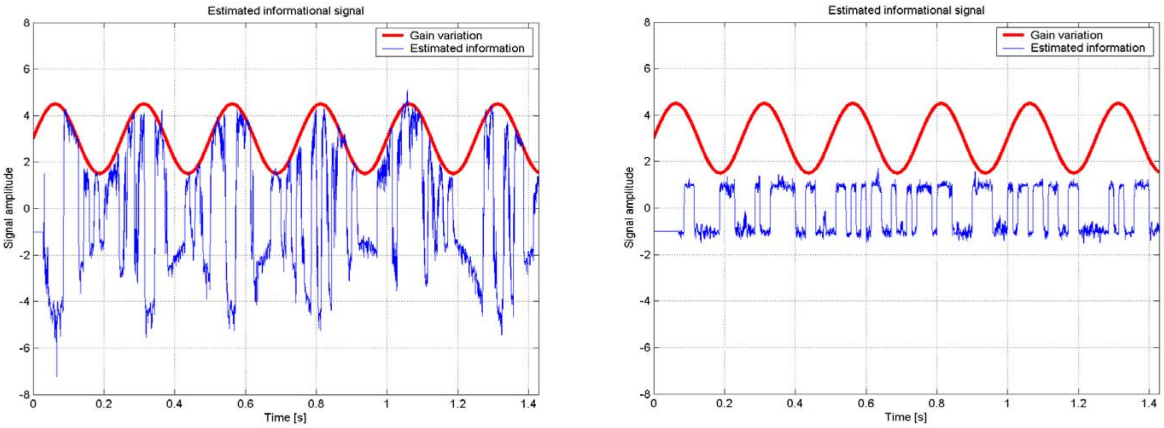

Fig. 5. Estimated information and channel gain for: a) modified system model; b) adaptive statistic loop

We can also observe on the synchronization diagram (figure 6 a) that estimated chaotic sequence remains well synchronized with the original spreading sequence used on the transmitter side.

The **second method** uses an adaptive gain control loop before the demodulator to adjust the dynamic range of the incoming signal, by matching the second order statistics of the estimated code $\hat{c}_k$ to that of the original spreading sequence. For example, in case of a *logistic* map, that it is characterized by a variation of 0.49, we can proceed to a proportional gain control using the following recursive equation:

$$G_{k+1} = G_k \frac{0.49}{E\{\hat{c}_k^2\}} \tag{9}$$

This control loop enables to track the inverse channel gain at the symbol rate; as a consequence, the lower the fluctuation rate of the channel gain will be with respect to the symbol frequency, the better the gain tracking performances will be.

Contrary to the modified dynamics method, the estimated information does not suffer from any significant magnitude variations; the influence of the channel gain is almost completely compensated by this gain control loop, a confirmation being given by the more clear aspect of the syncronization diagram (figure 6 b). This conclusion also can be observed in figure 7 b), where the coefficient G_k follows accuratly the variations of the inverse channel gain.

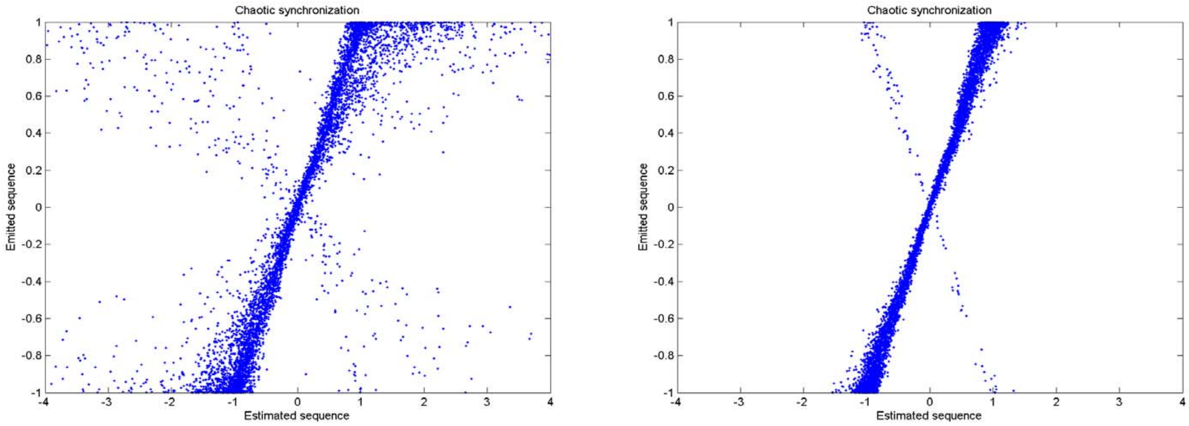

Fig. 6. Synchronization diagram for: a) modified system model; b) adaptive statistic loop

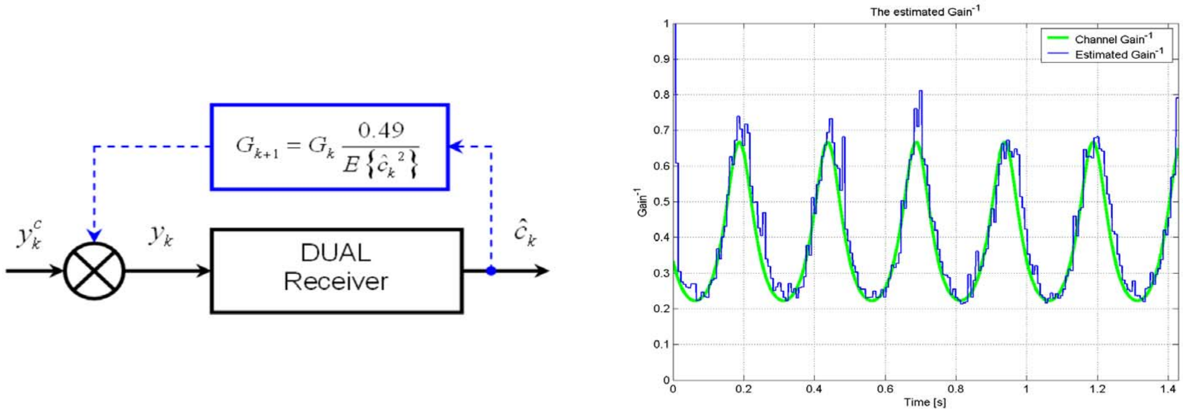

Fig. 7. a) Block diagram for the statistical gain control loop; b) Estimated G parameter and the inverse channel gain

To measure the performances of the both power control methods and to see the influence of the channel gain on an uncompensated dual *Unscented Kalman* receiver we have used a stationary channel with the relative gain varying in the interval [0.2,3] at a SNR of 30 dB. This high SNR has been used in order to neglect the influence of the channel noise and, as a consequence, to have a pertinent evaluation of the proposed gain control methods.

The Mean Squared Error of synchronization between the original spreading code and the code estimated on the receiver side have been used to measure the efficiency of the gain control methods. With no gain control, the dual Unscented Kalman receiver is characterized by a very small MSE around the unitary transfer coefficient, and for a slight change in the gain value, the system rapidly becomes unsynchronized. The receiver using the modified characteristic function (first method) works also well near the unitary gain and compensates also for greater values but diverges for smaller ones. The channel gain has almost no influence on the receiver relying on the statistical gain control loop (second method); such an automatic gain control can operate successfully for almost any channel gain variation. The limit is achived when the channel has a rapid variation during a symbol period, making thus a false variance estimation of the estimated code.

IV. CONCLUSIONS

The problem of automatic gain control in chaos based digital receivers has been considered in this paper. Large errors in synchronizing chaotic waveforms and then poor performances of the receiver can occur if no gain control strategy is applied on realistic channels. Two methods have been

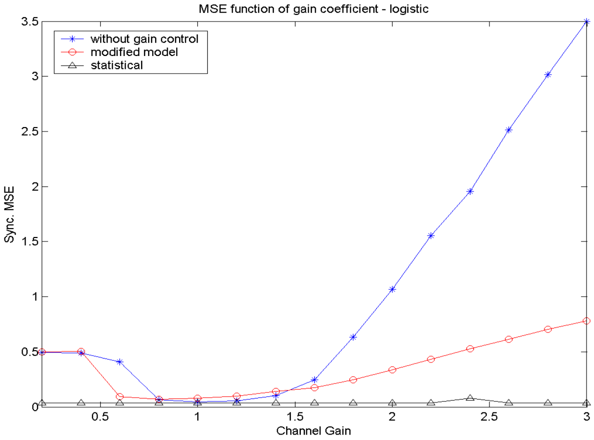

Fig. 8. MSE as a gain performance measure

proposed here for application to a dual Kalman filtering Chaotic Direct Sequence Spread Spectrum receiver. The first approach rely on a modification of the chaotic dynamical model in order to limit the range of the code estimates; the second method achieves the gain control by matching the second order statistics of the estimated code with that of the original spreading code, through a proportionate control loop. The synchronization MSE is employed to evaluate the efficiency of the two methods; the case of a receiver with no gain control is also considered in order to measure the performance improvement. The statistical gain control method has shown the better performances; the incoming signal power fluctuations is almost fully removed when using this approach.

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