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# Joint blind equalization and detection in chaotic communication systems using simulation-based methods

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ABSTRACT

In this paper an importance sampling (IS)-based technique is proposed to achieve the blind equalizer and detector for chaotic communication systems. Chaotic signals are generated using nonlinear dynamical systems. These signals have wide applications in communication as a result of their appropriate properties such as pseudo-randomness, large bandwidth, and unpredictability for long time. Based on the different chaotic signal properties, different communication methods such as chaotic modulation, masking, and spread spectrum have been proposed before. In this paper, chaos masking is adopted for transmitting modulated message symbols over an unknown channel, in which the joint demodulation and equalization is a nonlinear problem. Several methods such as extended Kalman filter (EKF), particle filter (PF), minimum nonlinear prediction error (MNPE), have been previously presented for this problem. Here, a new approach, based on Monte Carlo sampling, is proposed to joint channel equalization and demodulation. At the receiver end, importance sampling is used to detect binary symbols according to maximum likelihood (ML) criterion. Simulation results show that the proposed method has better performance, compared to existing methods, especially at low SNR.

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## 1. Introduction

Different applications of chaos in various fields of engineering such as communication, control, signal processing, etc. have attracted the attention of researchers for a long time [1,2]. Particularly, chaotic communication has been paid attention recently for several applications including multicarrier communication [3], spread spectrum [4], high data rate communication [5] etc. Researchers concentrate on application of chaos in communications and signal processing to extend nonlinear methods. A chaotic signal is produced via deterministic nonlinear dynamic system but has pseudo-random behaviour. Chaotic signals are too sensitive to initial conditions. Two signal trajectories related to two close initial points will diverge after a few steps. Chaotic signals have useful properties for utilizing in communication systems. Broadband spectrum, low cross-correlation with other signals, and impossible regeneration without knowing the initial value are some properties of chaotic signals that are required for spread spectrum, multiuser communication and cryptography, respectively [1,6].

In most of researches in chaotic communications, it is assumed that the transmitter is connected to receiver with ideal channel. However, for real communication systems the signal is affected by various types of distortion such as noise, fading and multipath interference during transmission. Usually, channel equalization is needed to compensate the channel distortion. The main purpose of channel equalization is to enhance the demodulation performance. In practical cases, channels parameters are unknown. Therefore, channel equalization is done solely using corrupted signal. In the case of no training data, the equalization process is called blind channel equalization. In chaotic communications, the conventional statistical method for equalization cannot necessarily provide acceptable performance due to the deterministic nature of chaotic signals. Some blind chaotic equalization methods based on different chaotic signal properties are presented in literature. An unscented Kalman filter-based method for blind equalization of chaotic spread spectrum system is introduced in Ref. [7]. In Ref. [8], an identification method by exploiting the short time predictability of chaotic signals is proposed. The technique is called minimum nonlinear prediction error (MNPE). This method has presented good performance in channels with autoregressive (AR) model. Synchronized based method to estimate and track channel state in multipath fading environment is studied in [9,10]. In Ref. [11] a complicated notion that is called phase space volume (PSV)

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is introduced and a new equalization algorithm using the infinite dimension of chaotic signal is presented. Afterwards, channel estimation problem has been formulated as an optimization problem in which the phase space volume objective function is minimized. This method called minimum phase space volume (MPSV). In Ref. [12] a blind equalization method based on the radial basis function network is proposed. Assuming a specific model for channel coefficients (e.g., AR), blind channel equalization can be formulated as a mixed parameter and state estimation problem.

Nonlinear filters such as extended Kalman filter (EKF) have ability to estimate both parameters and states of the systems. EKF for state estimation in chaotic systems has been used in Ref. [13] for the first time. Using the EKF for chaotic system equalization is proposed in Ref. [14]. The stability of EKF in chaotic equalization is investigated in Ref. [15]. EKF-based adaptive equalization for chaotic communication is presented in Ref. [16]. However, it is shown in Ref. [17] that the stability of this method is not always guaranteed. EKF is also used for chaotic demodulation [18,19] and combination of both equalization and demodulation in Ref. [11].

On the other hand, particle filtering (PF) as a well-known method for nonlinear filtering, is considered for using in chaotic communication systems. In particle filtering, the probability density function (PDF) of state variables is sequentially approximated using the properly generated random samples. It should be noted that particle filtering is a special case of more general methods called simulation based methods. In Ref. [20] a blind equalization and in Refs. [21–23] some methods for chaotic demodulation are presented based on the particle filtering.

In this paper, a joint blind equalization and demodulation method is proposed for using in chaotic communication systems. The method is based on importance sampling (IS), which is one of the most famous methods in random sampling literature. Assuming binary symbols are transmitted via chaos masking modulation, the conditional probability of received data, given each of binary symbols, is calculated through importance sampling. Therefore, the conditional likelihood values (given each symbol) can be evaluated and compared together for decision making at receiver. Actually, the maximum likelihood (ML) receiver can be implemented with this manner. Simulation results show that proposed method has better performance compared to other methods such as the EKF and the PF, especially for low SNR.

The rest of the paper is organized as follows. Chaotic communication and problem formulation are explained in Section 2. In Section 3, after a short introduction to importance sampling, the proposed blind equalization and detection is introduced. Section 4 is dedicated to simulation results and finally, the paper is concluded in Section 5.

## 2. Chaotic communication and problem formulation

Assume that the carrier of a transmitter is specified by one dimensional chaotic map, as below:

$$x_n = f(x_{n-1}, \lambda) \tag{1}$$

where $\lambda$ is a parameter which controls the bifurcation and transition to the chaotic behaviour of produced signal and is called bifurcation parameter. Additive chaos masking (ACM), is a type of chaotic modulation wherein the modulated symbol defined as:

$$z_n = x_n + s_n \tag{2}$$

in which $s_n$ is message signal. Another type of chaos modulation is multiplicative chaos masking (MCM) scheme where the transmitted signal is:

$$z_n = x_n s_n \tag{3}$$

In chaos masking, generally, $s_n$ is constant for $T$ successive $x_n$. Therefore it can be assumed that the signal spectrum is spread by factor $T$.

Assuming a discrete model for communication channel, the received signal can be modelled as:

$$y_n = \sum_{i=1}^{L} \alpha_n^i z_{n-i} + \upsilon_n \tag{4}$$

where $\upsilon_n$ is sample of a zero mean noise process and $\alpha_n^i$'s are channel coefficients. The subscript $n$ shows that the channel coefficients can be time variant in general.

State space is a standard method to represent a dynamic system. To make a state space description, one way is to model the message signal as an autoregressive (AR) model as follows [11,17]:

$$s_n = \sum_{i=1}^{p_s} a_i^s s_{n-i} + w_n \tag{5}$$

where $w_n$ is a white Gaussian noise, $\alpha_i^i{}'s$ are AR coefficients and $p_s$ is the order of the AR model. Hereafter, we assume that $s_n$ is modelled as a simple AR model with order of one according to (6).

$$s_n = s_{n-1} + w_n \tag{6}$$

For slowly time-varying communication channel, it is also convenient to assume an autoregressive model for channel coefficients $\alpha_i^n$ as follows:

$$\alpha_n^i = \sum_{k=1}^{p_\alpha} c_k^i \alpha_{n-k}^i + \zeta_n^i \tag{7}$$

where $\zeta_n^i$, $c_k^i$ and $p_\alpha$ are additive Gaussian noise, corresponding coefficients and the order of AR model, respectively. Again, we assume that $\alpha_n^i$ is modelled as a simple AR model with order of 1:

$$\alpha_n^i = \alpha_{n-1}^i + \zeta_n^i \tag{8}$$

By defining the $\boldsymbol{\alpha}_n = \left[\alpha_n^1, \alpha_n^2, \ldots, \alpha_n^{p_\alpha}\right]$, and $\boldsymbol{\zeta}_{n-1} = \left[\zeta_n^1, \zeta_n^2, \ldots, \zeta_n^{p_\alpha}\right]$, the extended state vector can be defined as:

$$\boldsymbol{x}_n = [x_n, s_n, \boldsymbol{\alpha}_n]^{\mathrm{T}} \tag{9}$$

Accordingly, we can form a state space model for communication system as follows:

$$\begin{cases} \boldsymbol{x}_n = F(\boldsymbol{x}_{n-1}) + \boldsymbol{W}_n \\ y_n = H(\boldsymbol{x}_n) + V_n \end{cases} \tag{10}$$

where $H(\boldsymbol{x}_n) = \sum_{i=1}^{L} \alpha_n^i z_{n-i}$ is determined based on the employed modulation scheme and channel effects. Also we have

$$F(\boldsymbol{x}_{n-1}) = [f(x_{n-1}), s_{n-1}, \boldsymbol{\alpha}_{n-1}]^{\mathrm{T}} \tag{11}$$

$\boldsymbol{W}_n = \left[0, w_{n-1}, \boldsymbol{\zeta}_{n-1}\right]$ and $V_n = \upsilon_n$ are system noise vector and observation noise vector, which are zero-mean Gaussian random vectors with covariance matrix $Q_n$ and $R_n$, respectively.

## 3. Blind detection and equalization in chaotic communication systems

At the receiver side, both the detection and equalization processes can be performed by estimating $\mathbf{x}_n$. Due to nonlinear behaviour of state and observation equations, appropriate methods must be adopted for such estimation. A well-known method is EKF in which a local linearization of equation is employed to achieve a linear state space description. In Refs. [11,16] EKF is proposed for

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