BLIND SOURCE SEPARATION AND EQUALIZATION OF MULTIPLE-INPUT MULTIPLE-OUTPUT FIR CHANNELS FOR CHAOTIC COMMUNICATION SYSTEMS

Gökçen Çetinel, Cabir Vural

Electrical- Electronics Engineering Department, Sakarya University
54187 Esentepe, Sakarya, Turkey
phone: + (90)-02642955813, fax: + (90)-02642955601, email: gcetinel@sakarya.edu.tr, cvural@sakarya.edu.tr
www.sakarya.edu.tr

ABSTRACT

In the last two decades, various blind channel equalization algorithms for chaotic communications systems have been developed by exploiting properties peculiar to chaotic signals. Almost in all of these algorithms, however, the propagation channel is assumed to be a single-input single-output (SISO) system. As far as we know, there is no study for multiple-input multiple-output (MIMO) unknown channel case. In this study, we propose a blind MIMO finite impulse response (FIR) channel equalization algorithm for chaotic communication systems. In MIMO communication systems, in addition to intersymbol interference (ISI), multiuser interference (MUI) is an important factor that hinders the detector performance. To increase the detector performance and achieve reliable, high-speed communication, proposed MIMO FIR channel equalization algorithm overcomes both ISI and MUI. Also, an optimum fixed filter that minimizes the mean square error (MSE) between chaotic input signals and equalizer outputs is designed. Since there do not exists a method for comparison, the proposed method is compared to the optimum fixed filter. Computer simulations show that the proposed algorithm gives results very close to those of optimum fixed filter and is able to recover all channel inputs simultaneously.

1. INTRODUCTION

Chaos has received a great deal of attention during the last two decades from a variety of researchers, including matematicians, physicists and engineers. Researches are interested in chaos especially in the area of signal processing and communication for the development of non-linear communication techniques. Chaotic signals are irregular, aperiodic, uncorrelated and impossible to predict over longer times. Spread-spectrum communication, multiuser communication and secure communication (cryptography) are three important applications of chaos arising from these properties. Furthermore, impulse-like autocorrelation and low cross-correlation functions are characteristic properties of chaotic signals [1].

The majority of chaos-based applications have been developed to see whether the performance increase is possible compared to the classical communication systems. In chaotic communications, a chaotic sequence is transmitted from a propagation channel after being modulated by an information bearing signal. The propagation channel distorts the transmitted signal unless it is ideal. Hence, channel equalization must be performed so that the detector will not make an error when deciding on the bit that was transmitted. If the parameters of channel are unknown, as in the most of practical applications, only the received corrupted signal is utilized to perform channel equalization and this method is called blind channel equalization. Such methods offer potential improvements in system capacity by eliminating the training overhead.

Depending on the number of inputs and outputs channel equalization problem can be classified as SISO and MIMO channel equalization. Several chaotic blind equalization techniques that exploit the inherent properties of the transmitted chaotic signal have been developed for SISO chaotic communication systems, recently [2, 3, 4, 5]. There exist some MIMO channel equalization algorithms in the case of known channel [6, 7]. There is no blind MIMO channel equalization algorithm developed for chaotic communication systems.

In this study, an adaptive blind channel equalization algorithm is proposed for MIMO chaotic communication systems by modifiying the cost function used in SISO chaotic equalization algorithms. In MIMO communication systems, in addition to ISI, MUI is an important factor that hinders the detector performance. To increase the detector performance and achieve reliable, high-speed communication, proposed MIMO FIR channel equalization algorithm overcomes effects of ISI and MUI. An optimum fixed filter is developed for MIMO chaotic communication systems. Since there does not exist a method for comparison, the proposed algorithm is compared to the optimum fixed filter. That the adaptive MIMO equalizer estimates the input signals reliably and it gives results very close to that of the optimum fixed filter are shown via simulations.

The study is organized as follows. In Section II, MIMO chaotic communication system model is explained and the problem to be solved is introduced. Assuming that channel parameters are known, an optimum fixed filter that minimizes the MSE between chaotic input signals and equalizer outputs is designed in Section III. Proposed adaptive MIMO channel equalization algorithm is derived in Section IV. In Section V,

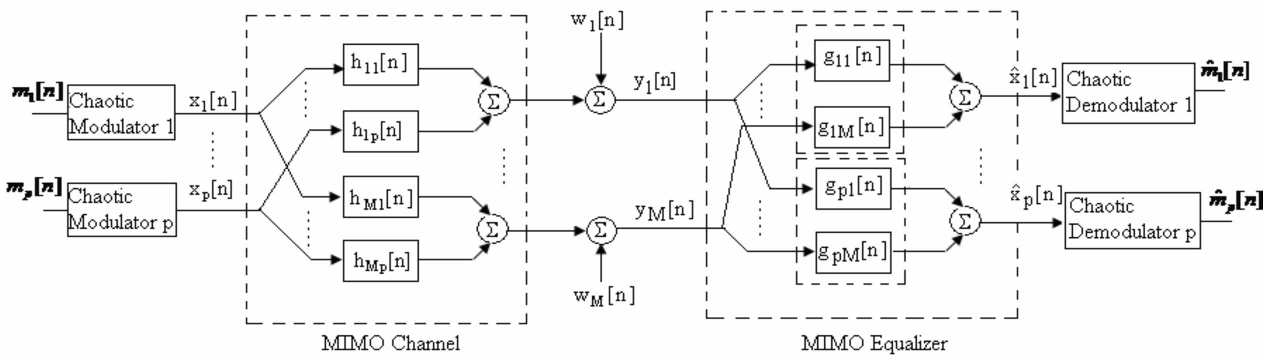

Figure 1. MIMO chaotic communication system model.

simulation results are provided to evaluate the effectiveness of proposed method and its performance is compared against the optimum fixed filter.

2. MIMO CHAOTIC COMMUNICATION SYSTEM AND PROBLEM FORMULATION

Consider a MIMO chaotic communication system shown in Figure 1. Information signals $m_j[n]$ are mapped to chaotic signals $x_j[n]$ via chaotic modulators and these chaotic signals are sent through different linear FIR systems with impulse responses $h_{ij}[n]$ for $i=1,\ldots, M$ and $j=1,\ldots, p$. Output of FIR filters are further contaminated by Additive White Gaussian Noises (AWGN) $w_i[n]$, before they reach to the receiver.

There exist several ways to generate chaotic information signal such as the tent, sawtooth, logistic or Chebyshev maps. In the literature, these maps are represented by a nonlinear dynamical equation given by $x[n]=f(x[n-1],\ldots,x[n-d])$, where d is called *embedding dimension* of the chaotic system.

Let the chaotic input signals vector $\hat{x}_j[n]$ at jth iteration at time n and channel impulse response coefficient vector $\boldsymbol{h}_{ij}$ be defined as

$$\boldsymbol{x}_j[n] := [x_j[n]\ x_j[n-1]\ \ldots\ x_j[n-L+1]]^T, j=1,2,\ldots,p \quad (1)$$

$$\boldsymbol{h}_{ij} := [h_{ij}[0]\ h_{ij}[1]\ \ldots\ h_{ij}[L-1]]^T,\ i=1,2,\ldots,M \quad (2)$$

By these definitions, i.th received signal at time n can be expressed as

$$y_i[n] = \sum_{j=1}^{p} \boldsymbol{h}_{ij}^T\ \boldsymbol{x}_j[n] + w_i[n] \quad , i=1,2,\ldots,M \quad (3)$$

where $w_i[n]$ is the i.th AWGN component at time n. Note that, i.th received signal at time n is a combination of p chaotic input signals. This contribution resulting from other users is called as multiuser interference (MUI). Hence both the ISI and MUI must be eliminated to decide the symbol that was transmitted. This process is known as channel equalization for MIMO systems.

As shown in Figure 1, a linear MIMO equalizer that consists of FIR filters of length K is implemented to recover chaotic input signals from M corrupted received signal. To express equalizer outputs with respect to received signal and equalizer coefficients, received signal vector at the output of channel can be written as

$$\boldsymbol{y}[n] = \left[y_1[n]\ldots y_M[n]\ldots y_1[n-K+1]\ldots y_M[n-K+1]\right] \quad (4)$$

Received signal vector must be written in terms of channel coefficients and chaotic input signals. Let the channel coefficient matrix $\mathbf{H}$, chaotic input signals vector $\boldsymbol{x}[n]$ and noise vector $\boldsymbol{w}[n]$ at time n be defined as

$$\mathbf{H} := \begin{bmatrix} \mathbf{H}[0] & \mathbf{H}[L-1] & \ldots & 0 \\ \vdots & \mathbf{H}[0] & \mathbf{H}[L-1] & 0 \\ 0 & \ldots & \mathbf{H}[0] & \mathbf{H}[L-1] \end{bmatrix}^T, \mathbf{H}[n] := \begin{bmatrix} h_{11}[n] \cdots h_{1p}[n] \\ \vdots \qquad \vdots \\ h_{M1}[n] \cdots h_{Mp}[n] \end{bmatrix} \quad (5)$$

$$\boldsymbol{x}[n] := [x_1[n]\ldots x_p[n],\ldots,x_1[n-K-L+2]\ldots x_p[n-K-L+2]] \quad (6)$$

$$\boldsymbol{w}[n] := [w_1[n]\cdots w_M[n]\cdots w_1[n-K+1]\cdots w_M[n-K+1]] \quad (7)$$

Then similar to the SISO case, received signal vector at time n can be expressed as

$$\boldsymbol{y}[n] = \boldsymbol{x}[n]\mathbf{H} + \boldsymbol{w}[n] \quad (8)$$

Now, the relation between estimated signals and received signals can be written in vector-matrix notation by adopting the same procedure in expressing the relation between received signal vector $\boldsymbol{y}[n]$ and transmitted signal vector $\boldsymbol{x}[n]$. Hence, let the equalizer output vector $\hat{\boldsymbol{x}}_j[n]$ and equalizer coefficient matrix $\mathbf{G}$ be defined as,

$$\hat{x}[n] := [\hat{x}_1[n]\ldots\hat{x}_p[n]] \quad (9)$$

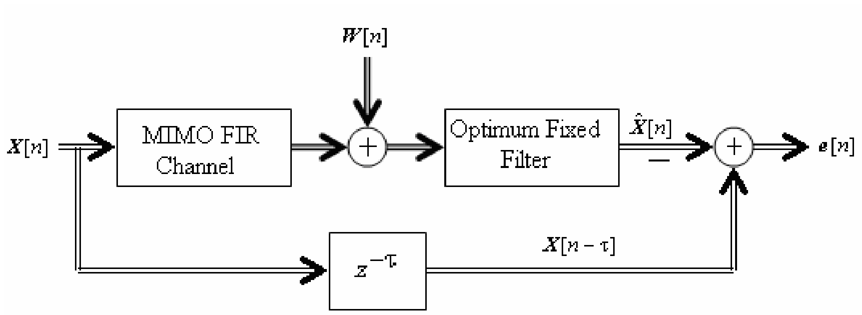

Figure 2. Definition of error function with channel noise in optimum fixed filter design.

$$\mathbf{G} := \left[\mathbf{G}[0]\ \mathbf{G}[1]\ ...\mathbf{G}[K-1]\right]^T,\ \mathbf{G}[n] := \begin{bmatrix} g_{11}[n] \cdots g_{1M}[n] \\ \vdots \qquad \vdots \\ g_{p1}[n] \cdots g_{pM}[n] \end{bmatrix}. \quad (10)$$

Then, the equalizer output at time n can be written as

$$\hat{\boldsymbol{x}}[n] = \boldsymbol{y}[n]\mathbf{G} \quad (11)$$

Substituting Equation (8) in Equation (11) yields

$$\hat{\boldsymbol{x}}[n] = \boldsymbol{x}[n]\mathbf{H}\,\mathbf{G} + \boldsymbol{w}[n]\mathbf{G} \quad (12)$$

The problem to be solved can be stated as follows: obtain estimates of chaotic input signals from received signals alone by designing an adaptive linear equalizer that is applied to the received signals. However, before doing that optimum fixed filter that minimizes the MSE between estimated signals at the output of equalizer and chaotic input signals is designed by assuming the channel parameters are known next.

3. OPTIMUM FIXED FILTER DESIGN

Consider the MIMO channel equalization problem in Figure 2. The objective is to recover chaotic input signals by designing an optimum fixed filter **G** that minimizes the MSE between equalizer output vector $\hat{\boldsymbol{x}}[n]$ and chaotic input signals vector $\boldsymbol{x}[n]$. Let redefine the equalizer output vector $\hat{\boldsymbol{x}}[n]$ and chaotic input signals vector $\boldsymbol{x}[n]$ as

$$\boldsymbol{x}[n] := [x_1[n], \ldots, x_p[n]] \quad (13)$$

$$\hat{\boldsymbol{x}}[n] := [\hat{x}_1[n], \ldots, \hat{x}_p[n]] \quad (14)$$

Perfect equalization ocurs when $\hat{\boldsymbol{x}}[n] = \alpha \boldsymbol{x}[n-\tau]$ where α is a real constant called *amplitude ambiguity* and τ is an integer called *delay ambiguity*. Our goal is to design **G** that minimizes $MSE = E[\|\boldsymbol{e}[n]\|^2]$, where $\boldsymbol{e}[n]$ is the estimation error vector defined as $\boldsymbol{e}[n] = \boldsymbol{x}[n-\tau] - \hat{\boldsymbol{x}}[n]$. For this purpose, the standard approach will be followed. First, MSE will be written in terms of the fixed filter. Then the stationary points (solutions that equate the derivative of the MSE equation with respect to **G** to zero) of the MSE equation are the possible solutions [8]. We will not attempt to derive the optimum fixed filter here since the space is limited. It can be easily shown that the optimum fixed filter that ensures the perfect equalization can be obtained as

$$\mathbf{G}^* = (\mathbf{H}^T \mathbf{X}[n]\mathbf{H} + \sigma_w^2 \mathbf{I})^{-1}(\mathbf{H}^T \mathbf{X}[n]\mathbf{G}_\tau) \quad (15)$$

where $\mathbf{X}[\mathrm{n}] = \boldsymbol{x}^T[n]\boldsymbol{x}[n]$, σ_w^2 is noise variance and **I** is identity matrix.

4. ADAPTIVE BLIND MIMO CHAOTIC CHANNEL EQUALIZATION ALGORITHM

As it clear from Eq. (15), design of the optimum equalizer requires knowledge of the channel, chaotic input signals and the noise variance which are not avaliable in a blind equalization setting. Hence, instead of an optimum fixed filter an adaptive equalizer must be built to recover chaotic input signals.

From Eq. (6), chaotic input signals vector $\boldsymbol{x}[n]$ is a combination of p input signals. From the relation between input signals and equalizer outputs given by Eq. (12), each of equalizer outputs is also a mixture of input signals. Therefore, in MIMO communication systems in addition to the ISI, MUI is an important factor that degrades the receiver performance. Hence, adaptive MIMO channel equalization algorithm must eliminate effects of both ISI and MUI and recover chaotic input signals from received signals alone.

In this section, similar to blind equalization methods for MIMO classical communication systems, a blind channel equalization algorithm is developed for MIMO chaotic communication systems by modifiying the cost function used in SISO chaotic equalization algorithms. A plausible cost function that overcomes effects of both ISI and MUI can be given by

$$J(\mathbf{G}) = \frac{1}{2}\sum_{i=1}^{p}(\hat{x}_i[n] - f(\hat{x}_i[n-1]))^2 + 2\sum_{\substack{i,j=1 \\ i\neq j}}^{p}\sum_{\delta_1}^{\delta_2}(\hat{x}_i[n]\hat{x}_j[n-\delta])^2 \quad (16)$$

The first term in Eq. (16) is the sum of nonlinear prediction errors of equalizer outputs and undo the effect of ISI as discussed in [9]. The second term indicates the cross-correlation between equalizer outputs and penalizes the contribution of other chaotic signals.

The cost function must be rewritten in terms of the equalizer coefficients to update the filter coefficients based on the Gradient Descent (GD) algorithm [8]. The general form of the GD algorithm for minimizing the proposed cost function is

$$\mathbf{G}_{k+1} = \mathbf{G}_k - \mu[\mathbf{\Lambda}_{1,k}(n)\ldots\mathbf{\Lambda}_{p,k}(n)] \tag{17}$$

where $\mathbf{\Lambda}_{i,k}(n)$ is derivative of cost function with respect to the equalizer coefficient matrix **G**. Derivation with respect to a matrix can be found in [8]. By using the chain rule of the derivative, $\mathbf{\Lambda}_{i,k}(n)$ can be written as

$$\begin{aligned}\mathbf{\Lambda}_{i,k}(n) &= (\hat{x}_{i,k}[n] - f(\hat{x}_{i,k}[n-1]))\boldsymbol{y}^{\boldsymbol{T}}[n] \\ &+ 4\sum_{\substack{i,j=1 \\ i\neq j}}^{p}\sum_{\delta_1}^{\delta_2}(\hat{x}_{i,k}[n]\hat{x}_{j,k}[n-\delta])\hat{x}_{j,k}[n-\delta]\,\boldsymbol{y}^{\boldsymbol{T}}[n]\end{aligned} \tag{18}$$

Substituting Eq. (18) in Eq. (17) yields the desired adaptive algorithm. The cross-correlation term in Eq. (18) $\hat{x}_{i,k}[n]\hat{x}_{j,k}[n-\delta]$, is calculated by using rectangular window. In other words, the value of the cross-correlation function is obtained from the past values of estimated signals according to the length of the window. The weight of the cross-correlation functions in Eq. (16) can be made variable. The parameters δ_1 and δ_2 are integers that should be chosen in compliance with the channel delay spread in order to take into account all the achievable delays between p user signals. μ is a small constant that should be chosen to ensure the algorithm stabilty.

5. SIMULATION RESULTS

In this section, two computer simulations are performed to evaluate the effectiveness of the proposed algorithm. Modulator and demodulator blocks shown in Figure 1 are ignored during simulations. It is assumed that chaotic input signals were generated using the logistic map with different initial values.

In the first experiment, the convergence properties of proposed MIMO chaotic blind channel equalization algorithm are investigated. Let the impulse response of the equalized system corresponding to the i-th chaotic input signal and j-th output of equalizer be

$$s_{ij}[n] := \sum_{m=1}^{M} g_{jm}[n] * h_{mi}[n] \quad i,j=1,\ldots,p. \tag{19}$$

The cross-correlation term in proposed algorithm goes to zero when $s_{12}[n] = s_{21}[n] = 0$. If this condition is satisfied, MIMO chaotic blind channel equalization algorithm is able to recover chaotic inputs signals [10].

MIMO channel is assumed to be a 2 input/ 3 output FIR system with impulse reponse given by

$$H[0] = \begin{pmatrix} -1.9522 & -0.5706 \\ -0.5666 & 0.4246 \\ -1.1293 & 0.7666 \end{pmatrix}, \quad H[1] = \begin{pmatrix} 1.0691 & -1.8841 \\ -0.7926 & 0.0598 \\ 0.3569 & -0.2744 \end{pmatrix} \tag{20}$$

Figure 3 shows the impulse response $s_{ij}[n]$ of the equalized system after 10000 iterations for $i=j=1$, 2. As can be seen from the figure, the condition $s_{12}[n] = s_{21}[n] = 0$ is almost satisfied. Hence, the two chaotic input signals are separated and the distortion is compensated. The first equalizer output recovers the first chaotic input signal and the second output recovers the second chaotic input signal.

In the second experiment, performance of the proposed algorithm is compared to that of optimum fixed filter. For this comparison, interference (IT) measure is used and defined as

$$IT_j = \frac{\sum_{i,n}\left|s_{ij}[n]\right|^2 - \max_{i,n}\left|s_{ij}[n]\right|^2}{\max_{i,n}\left|s_{ij}[n]\right|^2}, \quad j=1,\ldots,p. \tag{21}$$

In Eq. (21), $s_{ij}[n]$ is the impulse response of the equalized system corresponding to the i-th chaotic input signal and j-th output of the equalizer given by Eq. (19). Figure 4 illustrates the variation of interference during iterations for equalizer outputs $y_1[n]$ and $y_2[n]$ calculated by using the proposed algorithm and the optimum filter. The proposed algorithm gives results very close to those of the optimum fixed filter for both outputs.

6. CONCLUSIONS

In all of blind channel equalization algorithms developed for MIMO chaotic communication systems, propagation channel is assumed to be a SISO filter. In this study, a novel adaptive blind channel equalization algorithm is proposed for MIMO chaotic communication systems by modifying the cost function used in SISO chaotic channel equalization algorithms. Computer simulations show that the proposed adaptive algorithm is able to recover chaotic input signals simultaneously. Furthermore, the performance of the adaptive algorithm is compared to that of optimum fixed filter. The best results are obtained when the optimum fixed filter is used. The developed adaptive algorithm gives equalization results close to those of the optimum fixed filter even though it is based on the received signal alone.

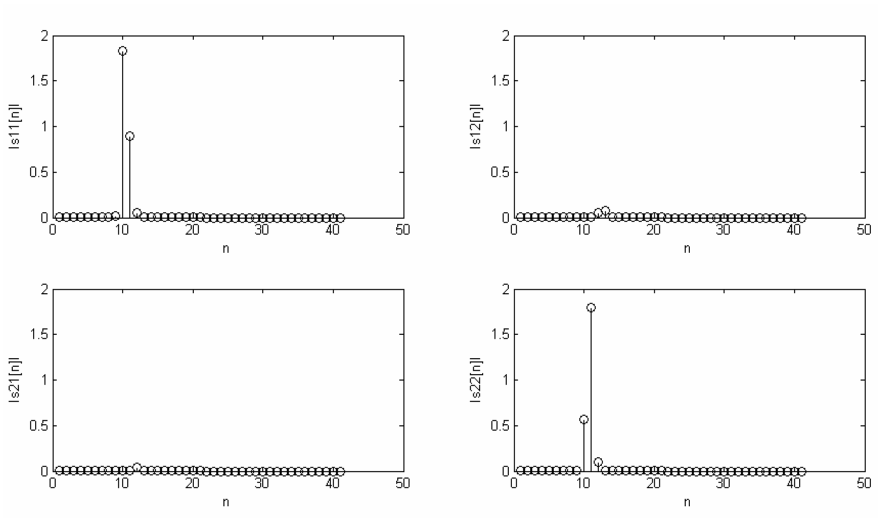

Figure 3. Impulse responses of the equalized system.

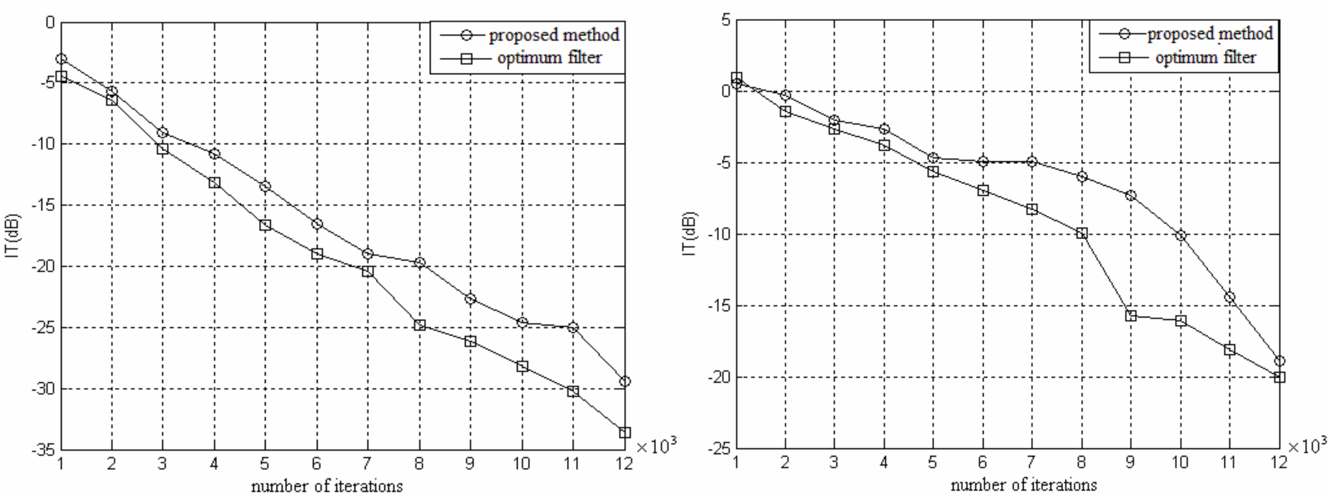

Figure 4. Interferences calculated by using the proposed algorithm and the optimum filter for equalizer outputs .

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