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Digital Signal Processing 16 (2006) 577–587
Digital Signal Processing
www.elsevier.com/locate/dsp

Decision-feedback equalization with fixed-lag smoothing in nonlinear channels

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Available online 16 March 2005

Abstract

Significant error rates are common in nonlinear communication and digital storage channels, due to nonlinear intersymbol interference (ISI). The decision-feedback equalizer (DFE) is often used to combat ISI, by providing nonlinear feedforward and feedback filters to compensate the nonlinear distortion. This paper presents recent work on a DFE that incorporates fixed-lag smoothing, termed the FLSDFE. We derive the FLSDFE estimator $\hat{X}_{t-n|t}$ for the case of binary-phase-shift keying inputs to a digital communication channel described by a truncated Volterra series. Simulation results are presented, showing the existence of 'resonance' phenomena within a state-space model of filtering-error propagation. The FLSDFE is shown to experience equalization performance that is strongly channel-dependent, highlighting a potential problem with robustness.
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1. Introduction

Nonlinearities in a communication or digital storage channel are known to increase error rates, due to nonlinear intersymbol interference (ISI) [1]. Decision-feedback equalizers (DFEs), using nonlinear feedforward and feedback filters, are often employed to combat ISI, with varying effectiveness. A recent paper introduced a blind DFE that incorporated

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1051-2004/$ – see front matter © 2005 Published by Elsevier Inc.
doi:10.1016/j.dsp.2005.01.008

fixed-lag smoothing [2], herein termed the FLSDFE (fixed-lag smoothing DFE). Intuitively, smoothing is expected to offer improved equalization performance, as we make use of more samples [3]. Additionally, by using a Volterra model [1,4–6], we might expect improved performance by more closely matching the intrinsic nonlinearity of a given communication channel. This paper provides evidence that the combination of fixed-lag smoothing with decision-feedback equalization may provide *worse* performance than might be expected, at least for some linear and nonlinear channels, and that the performance of the FLSDFE appears to be highly channel-dependent.

Our paper is organised as follows. Section 2 provides a derivation of the FLSDFE estimator $\hat{X}_{t-n|t}$ for the case of binary-phase-shift keying (BPSK) inputs to a communication channel described by a truncated Volterra series. In Section 3, we show via simulations that, for some channels and smoothing lags, the use of fixed-lag smoothing in the FLSDFE algorithm produces lower bit-error rates. For other channels and smoothing lags, however, we show that the FLSDFE may provide *worse* performance than might be expected, so that the performance of the FLSDFE appears to be highly channel-dependent. Finally, we illustrate the use of a particular state-space model in qualitative predictions of the performance of the FLSDFE algorithm on a given channel.

2. Derivation of FLSDFE for binary-phase-shift keying (BPSK)

Let $\{X_t\}$ and $\{Y_t\}$ represent the input and output baseband envelopes of a communication system, where $t \in \{\dots,-1,0,1,\dots\}$ is discrete-time. We regard X_t as a random symbol in $\mathcal{A}_2 = \{-1, 1\}$, the alphabet of BPSK [7]. Suppose X_t and Y_t are related by the pth-order Volterra series model [1,4–6],

$$Y_t = \sum_{k_1=0}^{N} h_1(k_1) X_{t-k_1} + \sum_{k_1=0}^{N} \sum_{k_2=k_1}^{N} h_2(k_1,k_2) X_{t-k_1} X_{t-k_2} + \sum_{k_1=0}^{N} \sum_{k_2=k_1}^{N} \dots \sum_{k_p=k_{p-1}}^{N} h_p(k_1,\dots,k_p) X_{t-k_1} \dots X_{t-k_p} + V_t, \tag{1}$$

of memory $N \in \{0,1,\dots\}$, with Volterra kernels $h_1(k_1), \dots, h_p(k_1,\dots,k_p)$. $\{V_t\}$ is independent and identically distributed, zero-mean Gaussian noise.

The problem we consider is the estimation of BPSK message symbol x_{t-n} at smoothing lag $n \in \{0,\dots,N\}$, given only the observed output sequence $\mathbf{y}_t = \{y_t, y_{t-1}, \dots\}$. We assume that the kernels $h_1(k_1), \dots, h_p(k_1,\dots,k_p)$ and noise variance σ_v^2 are fixed and known. Lowercase quantities x_t and y_t denote sample values of the random variables X_t and Y_t, respectively.

Consider the output Y_{t-k}, where $k \in \{0,\dots,n\}$ is an auxiliary lag index and $n \in \{0,\dots,N\}$ is the fixed smoothing lag of the FLSDFE. Since X_t is a random symbol in $\mathcal{A}_2$, observe that for $m \in \{1,2,\dots\}$, X_t^{2m} has the (degenerate) probability distribution

$$\mathbb{P}\big(X_t^{2m} = x_t^{2m}\big) = 1, \quad \forall x_t \in \mathcal{A}_2, \tag{2}$$

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