Signal Processing 89 (2009) 1359–1369

Contents lists available at ScienceDirect

Signal Processing

journal homepage: www.elsevier.com/locate/sigpro

Input–output identification of nonlinear channels using PSK, QAM and OFDM inputs

Gerasimos Mileounis [a,*], Panos Koukoulas [b], Nicholas Kalouptsidis [a]

[a] Department of Informatics and Telecommunications, University of Athens, Panepistimioupolis 157 84 Ilissia, Athens, Greece
[b] Electronics Division, Telecommunications Section, Hellenic Civil Aviation Authority, Ministry of Transport and Communications, 166 10 Glifada, Athens, Greece

ARTICLE INFO

Article history:
Received 9 August 2008
Received in revised form
24 December 2008
Accepted 7 January 2009
Available online 20 January 2009

Keywords:
Communication system nonlinearities
Volterra series
Identification
Higher order statistics
Orthogonal functions

ABSTRACT

Nonparametric identification of baseband and passband complex Volterra systems excited by communication inputs (phase shift keying, PSK; quadrature amplitude modulation, QAM and OFDM) is considered. Closed form expressions are established using multivariate orthogonal polynomials and higher order statistics. First multivariate orthogonal polynomials are used for baseband and passband Volterra models driven by PSK and QAM inputs and closed form expressions are derived. For baseband Volterra models excited with i.i.d. complex Gaussian signals (OFDM), the general $2p+1$ order Volterra system is solved using cross-cumulants in time and frequency domain. An order recursive algorithm is presented for the latter case, that does not require a priori knowledge of the systems order. Performance is illustrated by simulations.

1. Introduction

Nonlinear behavior is observed in several digital communication systems including satellite, high speed digital transmission over telephone channels and mobile cellular communications. In satellite communications, both the earth station and the satellite repeater employ power amplifiers such as traveling wave tube (TWT) amplifiers and solid state power amplifiers (SSPA). The satellite amplifier operates near saturation due to limited power resources and thus behaves in a nonlinear fashion [1]. Early satellite systems employed phase shift keying (PSK) modulation which was found to be less sensitive to nonlinearities than other more spectrally efficient modulation schemes, like quadrature amplitude modulation (QAM). The demand for high data rates and low bit error rates required by 3G and 4G mobile communication systems demonstrate the need for more spectrally efficient modulation methods that cope with the nonlinear phenomena. In mobile cellular communications, power amplifiers in hand held terminals are forced to operate in a nonlinear region to secure high power efficiency. Additional sources of nonlinear disturbance appear in hand held terminals where the loudspeaker and the microphone are placed near each other and have a relative small size (nonlinear acoustical echo). Mechanical vibrations of the enclosure are further sources of nonlinear distortion [2].

The wireless channel suffers from attenuation due to destructive addition of multipaths in the propagation media and due to interference from other users. The simple idea of increasing the transmitted energy to compensate for the effect of fading is not directly applicable because of the power limited environment. In high speed digital transmission over PSTN, nonlinear distortion is caused from inaccuracies in signal companding. In asymmetric digital subscriber line (ADSL), nonlinearities are introduced by the power amplifier and the metallic termination end of the transceiver module [3].

* Corresponding author. Tel.: +30 210 727 5340; fax: +30 210 727 5601.
E-mail addresses: gmil@di.uoa.gr (G. Mileounis), koukoula@di.uoa.gr (P. Koukoulas), kalou@di.uoa.gr (N. Kalouptsidis).

0165-1684/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.sigpro.2009.01.006

Many modern systems like ADSL, wireless LANs, terrestrial digital radio, digital video broadcasting and many forthcoming 3G and 4G mobile networks employ OFDM modulation. OFDM signals are vulnerable to nonlinearities due to high peak to average power ratio.

One of the most popular models that are applied for the description of the above nonlinear phenomena are Volterra systems [1,4,5]. In particular Wiener–Hammerstein models form a special class of Volterra systems where a static nonlinearity is sandwiched between two linear filters. In satellite applications the static nonlinearity describes the power amplifier, the single source of assumed nonlinearity. The linear filters include all filtering operations in both the transmitter and receiver with the linear channel filter.

Input–output identification of Volterra series using PSK, QAM and OFDM modulated inputs is the subject of this paper. Some of the results presented in this paper have been previously addressed in [6]. OFDM signals are obtained by the inverse discrete Fourier transform of PSK/QAM modulated i.i.d. sequences. It is known [7,8] that such OFDM sequences are approximately i.i.d. complex Gaussian signals. Identification of passband Volterra models via cross-correlation analysis is carried out in [9] for complex cyclostationary inputs and in [10] for PSK. The resulting closed form expressions rely on cross-correlations and the fact that the Volterra lag products of the input[1] are mutually orthogonal. It is shown in [11] that the estimates derived in [9,10] minimize the mean square error (MSE) (for PSK). In [12] the results obtained in [10] are extended to a cubic passband Volterra model excited with QAM. Baseband Volterra systems up to order 5 are considered in [13] by differentiating the MSE with respect to various Volterra kernels for both PSK and QAM. For OFDM signals the derived expressions in [14] are extended to a third order baseband Volterra [8].

Simple forms for the estimated kernels are possible only when Volterra lag products of the input are orthogonal to each other. This happens in the case of second order passband Volterra excited with Gaussian input [15], for arbitrary passband Volterra excited with complex cyclostationary input [9], for passband Volterra models excited with PSK [10] and for passband Volterra models not greater than three when excited with QAM [12]. This assumption is not necessary as shown in the paper. All previously cited papers examine passband nonlinear systems whereas we also consider baseband nonlinear systems.

In this work identification of passband and baseband Volterra systems relies on multivariate orthogonal polynomials. Multivariate orthogonal polynomials were initially introduced in [16] for real i.i.d. Gaussian sequences. Later on it was shown in [17], that these multivariate orthogonal polynomials are products of one-dimensional Hermite polynomials. Multivariate polynomials of separable type are also applicable to real white symmetrically distributed inputs [18–21]. Most of these works do not relate the orthogonal system kernels with the original Volterra kernels.

Multivariate orthogonal polynomials have been used in nonlinear communications for compensating channel distortions [4,5,22]. Previous efforts on the application of multivariate orthogonal polynomials for the identification of nonlinear channels have been reported in [23,24]. In [23] the theory of real multivariate orthogonal polynomials is discussed. Suboptimum closed form expressions based on the use of multivariate orthogonal polynomials for the special case of third order models are reported in [24].

In this paper the kernels of a general Volterra channel are estimated using orthogonal polynomials which are computed recursively through the determinant form of the Gram–Schmidt procedure [25]. This allows us to tackle passband systems excited by QAM of order greater than 3 (where the Volterra lag products of the input are not orthogonal to each other). More efficient estimates are obtained for baseband Volterra kernels of order greater than 3. The order of nonlinearity is assumed known.

Closed form expressions for the general $2p+1$ order baseband Volterra system with complex Gaussian input is given in time and frequency domain, without having to subtract the highest order nonlinearity each time to reduce the order of the Volterra model as in [8] for a third order model. A limitation of the algorithms described above is that the order of the nonlinear system must be known a priori, in practice this is rarely known. To cope with the order determination problem a recursive algorithm has been developed based on minimization of MSE.

The rest of the paper is organized as follows. Section 2 sets the necessary background and notation. The main results are given in Section 3 for PSK and QAM inputs and in Section 4 for OFDM inputs. Simulations are presented in Section 5. Conclusions and further work are discussed in Section 6.

2. Nonlinear communication channels and PSK–QAM–OFDM inputs

We shall consider Volterra models for the representation of nonlinear communication channels, following [1,4]. We shall allow a finite number of nonlinearities and finite system memory. Input and output signals are in general discrete complex valued sequences. A passband Volterra system has the form

$$y_n = \sum_{p=1}^{P} \sum_{\tau_1=0}^{N_p} \cdots \sum_{\tau_p=0}^{N_p} h_p(\tau_1, \ldots, \tau_p) \prod_{i=1}^{p} z_{n-\tau_i} + \eta_n \tag{1}$$

y_n denotes the system output, z_n the system input, η_n denotes the disturbance and h_p the Volterra kernel of order p. η_n is white complex Gaussian noise. P specifies the highest order of nonlinearity while N_p provides the pth order system memory. z_n and η_n are mutually independent.

[1] The pth order products of the input for a specific lag set $\tau_1, \ldots, \tau_p$ is referred as lag products of the input.