Signal Processing 128 (2016) 332–339

Contents lists available at ScienceDirect

Signal Processing

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

Short communication

DCT-based channel estimation for single- and multicarrier communications ☆

Fernando Cruz-Roldán [a,*], María Elena Domínguez-Jiménez [b], Gabriela Sansigre-Vidal [b], David Luengo [c], Marc Moonen [d]

[a] Department of Signal Theory and Communications (EPS), Universidad de Alcalá, 28805 Alcalá de Henares, Madrid, Spain
[b] Department of Mathematics Applied to Industrial Engineering (ETSII), Universidad Politécnica de Madrid, 28006 Madrid, Spain
[c] Department of Signal Theory and Communications (ETSIST), Universidad Politécnica de Madrid, 28031 Madrid, Spain
[d] Department of Electrical Engineering (ESAT-STADIUS), KU Leuven, 3001 Leuven, Belgium

ARTICLE INFO

Article history:
Received 19 November 2015
Received in revised form
7 April 2016
Accepted 1 May 2016
Available online 6 May 2016

Keywords:
Multicarrier modulation
Single carrier modulation
Channel estimation
Discrete cosine transform

ABSTRACT

We present a novel channel estimation technique based on discrete cosine transforms (DCT) for multicarrier and single carrier communications. Channel estimation is essential in communication systems, but especially in DCT-based transceivers for designing a front-end prefilter that must be included at the receiver to force the channel impulse response to be symmetric. The new technique is derived from the symmetric convolution-multiplication properties of discrete trigonometric transforms, and it is thus particularly suitable for DCT-based transceivers. The proposed channel estimation method is based on the use of training symbols, symmetric in time-domain, known by both transmitter and receiver. We demonstrate that by imposing a whole-sample symmetry condition in the training symbol, the channel impulse response can be estimated in a straightforward way. The analytical expressions to obtain the channel impulse response from the training symbol are also derived. Finally, this study is completed with several computer simulations to demonstrate the validity of the estimation technique.

1. Introduction

Multicarrier and single-carrier modulation (MCM and SCM) with redundant data are the dominant medium-access techniques in modern broadband communications. Discrete Fourier transform (DFT)-based systems are most popular for MCM and SCM due to their simplicity and robustness against multipath or frequency selectivity fading. Channel estimation has a significant influence on the system performance, and hence it is essential for receiver design for 4G and future 5G networks [1–4]. Several authors have studied channel estimation for DFT-based systems, and different approaches have been proposed in recent years, most of them collected in two interesting surveys [5,6].

Based on the fact that DFT-based systems present some drawbacks, such as high sidelobes or high sensitivity to timing and frequency offsets, the use of alternative block transforms to perform MCM or SCM has been recommended. Among them, the discrete cosine transform (DCT) has been proposed because it offers benefits such as excellent spectral compaction and energy concentration, less intercarrier interference leakage to adjacent subcarriers or that DCT uses only real arithmetic [7,8].

The conditions to use this transform for MCM with symmetric extension (SE), reported in [7,9,10], basically are that the number of redundant samples must be duplicated as prefix and suffix, and that the channel impulse response (CIR) must be symmetric, condition hardly satisfied in practice. To solve the latter problem, a front-end prefilter $\mathbf{h}_{pf}$ is included at the receiver, but the CIR must be estimated for its design. In this sense, the channel estimation is not only necessary to compensate for the channel effects, but also to construct this prefilter. Nevertheless, the channel estimation problem is not addressed in [7,9,10], and perfect channel knowledge is assumed. Furthermore, although several methods based on the use of DCT have been previously reported for this purpose (see, e.g., [11–14]), the goal of these DCT-based approaches is to get better channel estimates using the channel frequency response obtained from a preceding DFT. As a result, DCT is used to improve the accuracy of the channel estimate and thus the system performance, and two different transforms and additional circuitry are needed. To the best of our knowledge, designing a CIR estimation technique suitable for DCT-based transceivers is still an open problem, operating in realistic scenarios, in which the DCT is used

☆This work was partially supported by the Spanish Ministry of Economy and Competitiveness through projects TEC2015-64835-C3-1-R and TEC2012-38058-C03-01, and by the Spanish Ministry of Education, Culture and Sports through project PRX14/00147.

* Corresponding author.
E-mail address: fernando.cruz@uah.es (F. Cruz-Roldán).

http://dx.doi.org/10.1016/j.sigpro.2016.05.001
0165-1684/© 2016 Elsevier B.V. All rights reserved.

to perform a channel estimation and data demodulation.

Therefore, the aim of this paper is to present an efficient and simple DCT-based CIR estimation technique. We focus our attention on MCM, though the proposed solution also applies for SCM. Assuming that the time-domain channel $\mathbf{h}_{ch}$ can be modelled as an FIR filter, the proposed non-blind data aided channel estimation technique is based on the use of a whole-sample (WS) symmetric training symbol. We derive the formulation of the channel estimator for systems that employ a Type-IV even and Type-II even DCT (DCT4e and DCT2e), mainly motivated by their technological advantages (for more details refer to [7,10]). However, this study can be easily extended to other classes of DCTs.

The rest of the paper is organized as follows. In Section 2, we describe the system model. In Section 3, we precisely formulate the problem, deriving expressions to estimate the CIR for DCT2e- and DCT4e-based systems. Section 4 presents some simulation results to demonstrate the validity of the proposed technique and to compare it with other DFT-based systems. Finally, Section 5 contains the conclusion.

2. MCM system model

Fig. 1 shows the general block diagram representing the transceiver and the channel estimation stage herein considered. At the transmitter, the incoming data $\mathbf{X}$ are processed by an N-point inverse transform $\mathbf{T}_a^{-1}$, with N being the number of subchannels or subcarriers. Then, matrix $\mathbf{\Gamma}$ introduces redundant samples into each time-domain data symbol

$$\mathbf{x}_e = \mathbf{\Gamma}\cdot\mathbf{T}_a^{-1}\cdot\mathbf{X}$$

in order to force the linear convolution performed by the channel to become a different convolution in the samples of interest ($0 \le n \le (N-1)$), equivalent to an element-by-element operation in the corresponding transform domain.

Ignoring for the moment the channel estimation stage, the received data vector can be specified as

$$\mathbf{y} = \mathbf{H}\cdot\mathbf{x}_e + \mathbf{z},$$

where $\mathbf{H}$ is a Toeplitz matrix formed from $\mathbf{h} = \mathbf{h}_{ch*}\mathbf{h}_{pf}$, and $\mathbf{z}$ is a column vector related to the additive noise. At the receiver, an $\mathbf{\Upsilon}$ matrix is needed to select the samples of interest and to allow the channel matrix diagonalization:

$$\mathbf{H}_{equiv} = \mathbf{\Upsilon}\cdot\mathbf{H}\cdot\mathbf{\Gamma} = \mathbf{T}_c^{-1}\cdot\mathbf{D}\cdot\mathbf{T}_a,$$

where $\mathbf{D}$ is a diagonal matrix with elements d_i, $0 \le i \le (N-1)$. Next, a direct transform $\mathbf{T}_c$ is performed at the receiver

$$\mathbf{Y} = \mathbf{T}_c\cdot\mathbf{\Upsilon}\cdot\mathbf{y},$$

and the frequency domain equalization (FEQ) is carried out by means of one complex coefficient per subcarrier $1/d_i$.

In DMT and OFDM, $\mathbf{T}_a$ and $\mathbf{T}_c$ are DFTs. Furthermore, the insertion of redundancy, e.g., a cyclic prefix, allows the matrix $\mathbf{H}_{equiv}$ to be modelled as a right-circulant matrix, which can be expressed as

$$\mathbf{H}_{equiv} = \mathbf{W}^{-1}\cdot\mathbf{D}\cdot\mathbf{W}, \tag{1}$$

where $\mathbf{W}$ and $\mathbf{W}^{-1}$ are, respectively, the DFT and the IDFT matrix, and $\mathbf{D}$ is a diagonal matrix with elements d_i, obtained as the N-point DFT of the channel impulse response. For the alternative systems herein considered, $\mathbf{T}_a$ and $\mathbf{T}_c$ are DCT2e or DCT4e, such as is shown in [7,9,10]. For these transceivers, the insertion of SE as both prefix and suffix allows to convert $\mathbf{H}_{equiv}$ to the sum of a Toeplitz matrix and a Hankel matrix, which is diagonalized by the DCTs [7,10]. Table 1 includes the full definition of the matrices $\mathbf{\Gamma}$ and $\mathbf{\Upsilon}$ used in Fig. 1.

3. DCT-based channel estimation

Let $\mathbf{h}_{ch} = [h_0, \ldots, h_\nu]^T$ be the transmission channel of length $\nu + 1$, which is assumed known a priori in this paper, and let

$$\mathbf{x}^{ps} = \begin{bmatrix} x_M & \cdots & x_1 & x_0 & x_1 & \cdots & x_M & 0 & \cdots & 0 \end{bmatrix}$$

be the N-length training symbol to be transmitted. This symbol must present a WS symmetry in the nonzero samples, where $2M < N$ (see Fig. 2). Hereinafter, let us consider without loss of generality that $N = 2M + 2$. In this case, the $(N + 2M)$– length received data vector is given by

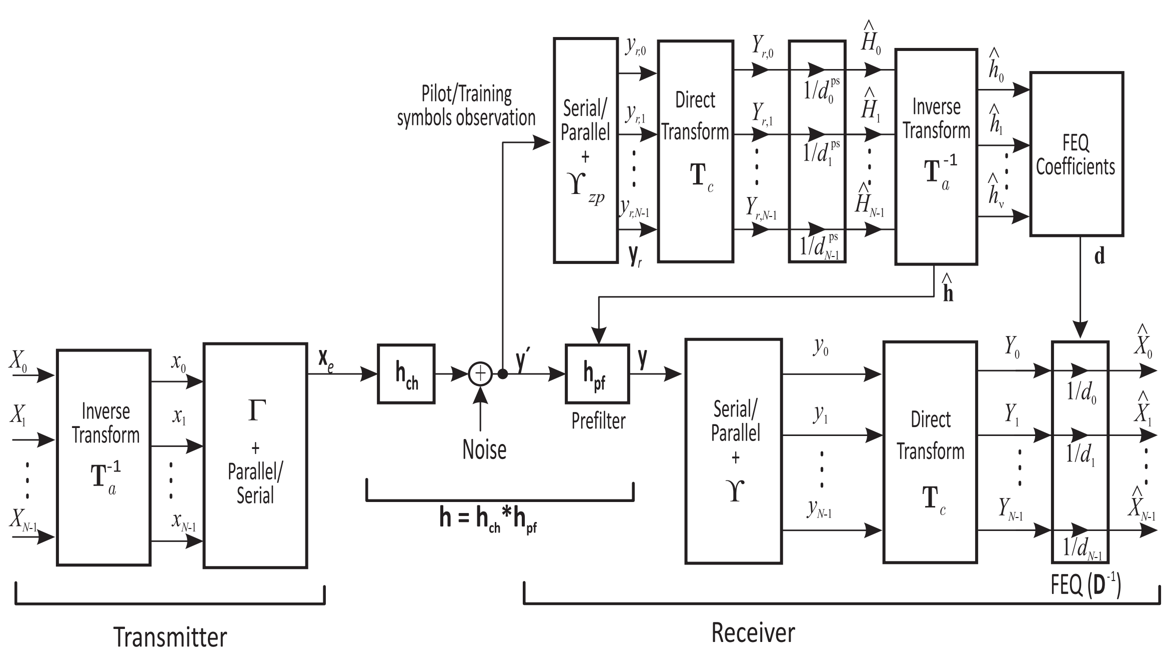

Fig. 1. Block diagram of the transceiver systems used in the simulations.