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Joint channel and phase noise estimation in OFDM systems at very high speeds

Jin Fang [a], Eric Pierre Simon [a,*], Marion Berbineau [b], Martine Lienard [a]

[a] IEMN/TELICE Laboratory, University of Lille, France
[b] Universite Lille Nord de France, INRETS, LEOST, F-59650 Villeneuve d'ascq, France

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ABSTRACT

In this paper, the problem of joint phase noise and channel estimation for OFDM systems over a fast time-varying frequency-selective channel is explored. Each channel tap time-variation within one OFDM symbol is approximated by a Basis Expansion Model (BEM). Joint estimation is performed on multiple OFDM symbols via the Extended Kalman Filtering in order to exploit the time-correlation of the parameters. The data symbols are estimated by means of an iterative pilot-based algorithm. It is shown that, with only 2 iterations, our algorithm outperforms the conventional one, and the performance approaches that of the ideal case for which the channel response and phase noise are known.

1. Introduction

Orthogonal frequency division multiplexing (OFDM) has become a standard technique for broadband high speed communication systems, mainly the Mobile Worldwide Interoperability Microwave Systems for Next-Generation Wireless Communication Systems (WiMAX) and the Third-Generation Partnership Project (3GPP) in the form of its Long-Term Evolution (LTE) project. However, it is well known that the OFDM modulation is very sensitive to synchronization errors, yielding severe degradation since it produces inter-carrier interference (ICI) and attenuates the desired signal.

In this paper, we propose an algorithm for tracking the phase noise (PHN) together with the channel taps in the presence of very high mobility. Several papers investigated joint PHN and channel estimation [1–3] for OFDM systems. In those papers, the channel is assumed constant within an OFDM symbol. More recently, [4] proposed an algorithm capable of dealing with the fast time-variations of the channel within an OFDM symbol. Handling very high mobility is a major challenge for future communications. Since the signal transmission under very high speed scenarios experiences serious degradation, it is crucial to develop effective new techniques for very high speed vehicular applications, such as high speed trains.

The algorithm of [4] is a basis expansion model (BEM) [5,6] based algorithm which performs minimum mean square error (MMSE) estimation separately for each received OFDM symbol. In other words, the parameters are estimated based only on the present received OFDM symbol $\mathbf{y}_k$. We propose here to perform estimation based on multiple OFDM symbols, i.e., our algorithm uses the complete data set $\left\{\mathbf{y}_0, \mathbf{y}_1, \ldots, \mathbf{y}_k\right\}$, which consists of the present and the past received OFDM symbols. In doing so, the algorithm is able to exploit the channel and PHN time correlation, which improves performance. This can be done by means of the extended Kalman filter [7].

This paper is organized as follows: Section 2 introduces the OFDM system with PHN and the BEM modeling. Section 3 describes the state model and the Extended Kalman Filter. Section 4 covers the algorithm for joint channel and PHN estimation together with data recovery. Section 5 presents the simulations results which validate our technique. Finally, our conclusions are presented in Section 6.

The notations adopted are as follows: Upper (lower) bold face letters denote matrices (column vectors). $[\mathbf{x}]_n$ denotes the nth element of the vector $\mathbf{x}$, and $[\mathbf{X}]_{n,m}$ denotes the $[n, m]$th element of the matrix $\mathbf{X}$. It is noteworthy that vector and matrix indices start from 0 and not from 1. $\mathbf{I}_N$ is a $N \times N$ identity matrix. diag{$\mathbf{x}$} is a diagonal matrix with $\mathbf{x}$ on its main diagonal, diag$\left\{\mathbf{X}\right\}$ is a vector whose elements are the elements of the main diagonal of $\mathbf{X}$ and blkdiag$\left\{\mathbf{X}, \mathbf{Y}\right\}$ is a block diagonal matrix with the matrices $\mathbf{X}$ and $\mathbf{Y}$ on its main diagonal. The superscripts $(\cdot)^T$ and $(\cdot)^H$ stand respectively for transpose and Hermitian operators. $\mathbb{E}_x[\,\cdot\,]$ is the expectation over x, $J_0(\cdot)$ is the zeroth-order Bessel function of the first kind and $\delta_{k,m}$ is the Kronecker symbol.

2. OFDM system description

2.1. OFDM system model

Consider an OFDM system with N sub-carriers, and a cyclic prefix length N_g. The duration of an OFDM symbol is $T = N_b T_s$, where T_s is

* Corresponding author.
E-mail address: eric.simon@univ-lille1.fr (E.P. Simon).

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the sampling time and $N_b = N + N_g$. Let $x_k[n]$, $n = -N/2, \ldots, N/2-1$ be the transmitted data symbol on the subcarrier n of the kth OFDM symbol. The $\{x_k[n]\}$ are normalized symbols (i.e., $\mathbb{E}[x_k[n]x_k^*[n]] = 1$).

We assume, without loss of generality, that PHN is present only at the front of the receiver [8]. Let $\phi(t)$ be the PHN process. It is modeled as a Wiener process [9], with the 3 dB bandwidth parameter Δf_{3dB}. In the following, we consider the sampled version of the PHN $\phi_k[q] = \phi(kT + qT_s)$.

After transmission over a multi-path Rayleigh channel and in the presence of PHN, the subcarrier n of the kth received OFDM symbol $y_k[n]$ is given in the frequency domain (after removing cyclic prefix and taking DFT) by [6,5]:

$$\mathbf{y}_k = \mathbf{H}_k \mathbf{x}_k + \mathbf{w}_k \tag{1}$$

where $\mathbf{x}_k = \left[x_k[-N/2], x_k[-N/2+1], \ldots, x_k[N/2-1]\right]^T$. $\mathbf{y}_k$ is defined in a similar way as $\mathbf{x}_k$. $\mathbf{w}_k$ is a white complex Gaussian noise vector of covariance matrix $\sigma^2 \mathbf{I}_N$ and $\mathbf{H}_k$ is the $N \times N$ channel matrix. The elements of $\mathbf{H}_k$ can be written as [10]:

$$[\mathbf{H}_k]_{n,m} = \frac{1}{N}\sum_{l=0}^{L-1}[e^{-j2\pi(m/N-1/2)l}\sum_{q=0}^{N-1}\alpha_{l,k}[q]e^{j2\pi(m-n/N)q}e^{j\phi_k[q]}] \tag{2}$$

where $\{\alpha_{l,k}[q] = \alpha_l(kT + qT_s), l = 0, \ldots, L-1\}$ are the channel taps and L is the length of the channel impulse response. These channel taps are wide-sense stationary (WSS), narrow-band zero-mean complex Gaussian processes of variances $\sigma^2_{\alpha_l}$ and with the so-called Jakes' power spectrum of maximum Doppler frequency f_d [11]. The average energy of the channel is normalized to one, i.e., $\sum_{l=0}^{L-1}\sigma^2_{\alpha_l} = 1$. Let us define the $N \times 1$ vector:

$$\boldsymbol{\alpha}_{l,k} = [\alpha_{l,k}[0], \ldots, \alpha_{l,k}[N-1]]^T \tag{3}$$

The correlation matrix of $\boldsymbol{\alpha}_{l,k}$ for the time-lag p, $\mathbf{R}^{(p)}_{\alpha_l} = \mathbb{E}\left[\boldsymbol{\alpha}_{l,k}\boldsymbol{\alpha}^H_{l,k-p}\right]$, is given by:

$$[\mathbf{R}^{(p)}_{\alpha_l}]_{n,m} = \sigma^2_{\alpha_l} J_0(2\pi f_d T_s(n - m + pN_b)) \tag{4}$$

2.2. Phase noise model

Reference [12] explains that an electronic component noise within the oscillator affects the shape of the oscillator output signal whose phase then deviates from the phase of the desired signal, yielding the PHN process. Its behaviour depends on the type of oscillator used, i.e., PLLs or free running oscillators. We consider in this paper free-running oscillators, for which the PHN is modelled as a continuous Brownian motion process[9]:

$$\phi_k[q] = \phi_k[q-1] + \nu_k[q], \ q = 0, \ldots, N-1 \tag{5}$$

where $\nu[q]$ is a Gaussian random variable with zero-mean and a variance $\sigma^2_\nu = 4\pi\Delta f_{3dB} T_s$. Stacking the N samples corresponding to the kth OFDM symbol in a vector $\boldsymbol{\phi}_k = [\phi_k[0], \ldots, \phi_k[N-1]]^T$, we obtain:

$$\boldsymbol{\phi}_k = \boldsymbol{\phi}_{k-1} + \mathbf{v}_k \tag{6}$$

where $\mathbf{v}_k$ is a Gaussian $N \times 1$ vector with zero-mean and a correlation matrix $\mathbf{V}$ (see Appendix A):

$$\mathbf{V} = \sigma^2_\nu \begin{pmatrix} N_b & N_b - 1 & \cdots & N_g + 1 \\ N_b - 1 & N_b & \cdots & N_g + 2 \\ \vdots & \vdots & \ddots & \vdots \\ N_g + 1 & N_g + 2 & \cdots & N_b \end{pmatrix} \tag{7}$$

2.3. BEM channel model

In each OFDM block, there are N samples to be estimated for each channel tap due to the fast time-variation of the channel, yielding a total of LN samples for the whole channel and for each block. In order to reduce the number of parameters to be estimated, we resort to the Basis Expansion Model (BEM). In this section, our aim is to accurately model the time-variation of $\alpha_{l,k}[q]$ from $q = 0$ to $N-1$ by using a BEM. The purpose of using a BEM is to approximate $\boldsymbol{\alpha}_{l,k}$ as the weighted sum of just a few basis function $\mathbf{b}_d$, as follows:

$$\boldsymbol{\alpha}_{l,k} = \mathbf{B} \cdot \mathbf{c}_{l,k} + \boldsymbol{\xi}_{l,k} \tag{8}$$

where $\mathbf{B} = [\mathbf{b}_0, \ldots, \mathbf{b}_{D-1}]$ is a $N \times D$ matrix that collects the D basis functions $\mathbf{b}_d$. Vector $\mathbf{c}_{l,k} = [c_{l,k}[0], \ldots, c_{l,k}[D-1]]^T$ represents the D BEM coefficients for the lth channel tap of the kth OFDM symbol, and $\boldsymbol{\xi}_{l,k}$ represents the corresponding BEM modeling error, which is assumed to be minimized in the mean square error (MSE) sense [13]. Under this criterion, the optimal BEM coefficients and the corresponding model error are given by:

$$\mathbf{c}_{l,k} = \left(\mathbf{B}^H\mathbf{B}\right)^{-1}\mathbf{B}^H\boldsymbol{\alpha}_{l,k} \tag{9}$$

$$\boldsymbol{\xi}_{l,k} = (\mathbf{I}_N - \mathbf{S})\boldsymbol{\alpha}_{l,k} \tag{10}$$

where $\mathbf{S} = \mathbf{B}\left(\mathbf{B}^H\mathbf{B}\right)^{-1}\mathbf{B}^H$ is a $N \times N$ matrix.

Various traditional BEM designs have been reported to model the channel time-variations, e.g., the Complex Exponential BEM (CE-BEM), the Polynomial BEM (P-BEM) or the Karhuen–Loeve BEM (DKL-BEM) for instance [5,14].

From now on, we can describe the OFDM system model derived previously in terms of the BEM. Substituting (8) in (1) yields after some algebra:

$$\mathbf{y}_k = \mathbf{H}_k(\boldsymbol{\phi}_k) \cdot \mathbf{c}_k + \boldsymbol{\epsilon}_k + \mathbf{w}_k \tag{11}$$

where the $LD \times 1$ vector $\mathbf{c}_k$ and the $N \times LD$ matrix $\mathbf{H}_k$ are given by:

$$\begin{aligned} \mathbf{c}_k &= \left[\mathbf{c}^T_{0,k}, \ldots, \mathbf{c}^T_{L-1,k}\right]^T \\ \mathbf{H}_k(\boldsymbol{\phi}_k) &= \frac{1}{N}\left[\mathbf{Z}_{0,k}(\boldsymbol{\phi}_k), \ldots, \mathbf{Z}_{L-1,k}(\boldsymbol{\phi}_k)\right] \end{aligned} \tag{12}$$

$$\begin{aligned} \mathbf{Z}_{l,k}(\boldsymbol{\phi}_k) &= \left[\mathbf{M}_0(\boldsymbol{\phi}_k)\ \mathrm{diag}\{\mathbf{x}_k\}\ \mathbf{f}_l, \ldots,\right. \\ &\quad \left.\mathbf{M}_{D-1}(\boldsymbol{\phi}_k)\ \mathrm{diag}\{\mathbf{x}_k\}\ \mathbf{f}_l\right] \end{aligned} \tag{13}$$

where vector $\mathbf{f}_l$ is the lth column of the $N \times L$ Fourier matrix $\mathbf{F}$, and $\mathbf{M}_d(\boldsymbol{\phi}_k)$ is a $N \times N$ matrix given by:

$$[\mathbf{F}]_{n,l} = e^{-j2\pi(n/N-1/2)l} \tag{14}$$

$$\left[\mathbf{M}_d(\boldsymbol{\phi}_k)\right]_{n,m} = \sum_{q=0}^{N-1}[\mathbf{B}]_{q,d}\ e^{j2\pi(m-n/N)q}e^{j\phi_k[q]} \tag{15}$$

The second component in (11), ϵ_k, represents the approximation error in the observation model.

3. AR model and extended Kalman filter

3.1. The AR model for $\mathbf{c}_k$

From (9), we get that the optimal BEM coefficients $\mathbf{c}_{l,k}$ are correlated complex Gaussian variables with zero-means and correlation matrix given by:

$$\begin{aligned} \mathbf{R}^{(p)}_{\mathbf{c}_l} &= \mathrm{E}[\mathbf{c}_{l,k}\mathbf{c}^H_{l,k-p}] \\ &= \left(\mathbf{B}^H\mathbf{B}\right)^{-1}\mathbf{B}^H\mathbf{R}^{(p)}_{\alpha_l}\mathbf{B}\left(\mathbf{B}^H\mathbf{B}\right)^{-1} \end{aligned} \tag{16}$$