

# ICI Estimation of MIMO OFDM Systems

M s Gayatri Pal Department of Electronics & communication, Truba College of Technology & Science, Indore

## Abstract

Orthogonal Frequency Division Multiplexing (OFDM) is a multi-channel modulation technique that makes use of Frequency division multiplexing (FDM) being modulated by a low bit rate digital stream. The main reason of using OFDM is because here the symbol detection is easy and also to increase the robustness against frequency selective fading and narrow band interference. In scenarios with time-varying channels such as intelligent traffic systems or high speed trains, the orthogonality between subcarriers in orthogonal frequency division multiplexing (OFDM) is destroyed leading to inter-carrier interference (ICI). In the literature, ICI equalization algorithms have been discussed; however, they assume perfect channel knowledge at sample level. Unfortunately, existing channel estimation algorithms do not provide accurate channel estimates at high Doppler spreads, prohibiting data transmission with high spectral efficiency. In this paper, we studied an algorithm for ICI estimation that can be applied to OFDM systems with an arbitrary pilot structure. ICI estimator models the channel variation by means of a basis expansion model (BEM).

## Introduction

Orthogonal Frequency Division Multiplexing (OFDM) has become the selected transmission technique for several recent wireless standards, such as the IEEE standard for local and metropolitan area networks (better known as WiMAX), or the 3GPP UTRA Long Term Evolution (LTE). In OFDM, the transmission bandwidth is divided into multiple narrowband subcarriers. By the addition of a proper cyclic prefix (CP), these subcarriers become fully orthogonal and experience frequency flat fading conditions in time-invariant channels. This allows for simple equalization of the signal at the receiver, while keeping a high spectral efficiency due to the use of orthogonal overlapping subcarriers. In OFDM systems with frequency re-use, however, the signal transmitted from other cells may create co-channel interference which, if not correctly treated, can induce a severe degradation of the receiver performance, especially at the cell edge.

Orthogonal frequency division multiplexing (OFDM) is used in most current and upcoming mobile communication systems. Such systems perform well when the channel is not varying during the duration of one OFDM symbol. However, mobile scenarios in which the channel is varying rapidly are becoming more and more important for intelligent traffic systems or high speed trains. If the channel is not constant during the transmission of one OFDM symbol, inter-carrier interference (ICI) occurs and the performance of the system

is degraded. Therefore, there is a need to introduce receivers that combat ICI. In [1], the ICI for single input single output (SISO) and multiple input multiple output (MIMO) transmissions is analyzed. Pilot symbols located at adjacent subcarriers in order to estimate the ICI. This approach is in contradiction to the common agreement that scattered pilot symbols are optimal [2, 3]. Nevertheless, such an approach would be suitable for ICI estimation in the case of a SISO system. In the case of a MIMO system, such a pilot symbol pattern results in a huge overhead. In [4–6] ICI estimation and mitigation assume that the channel is varying linearly in the time domain. We can use polynomials for channel estimation in MIMO. However, their estimator works only with a limited order of the polynomials. Numerous different equalization algorithms are proposed in [8–10], in which the authors assume perfect channel knowledge for each signal sample. However, this information is not available at the receiver and algorithms cannot estimate the time-variant channel impulse response at sample level precisely enough at high Doppler spreads.

The rest of this paper is organized as follows. Section II presents the system model. The channel estimation is presented in Sect. III. In section IV ICI estimation is discussed. Section V concludes this paper.

## I. SYSTEM MODEL

Long term evolution (LTE) is the current standard of the cellular communication 3rd Generation Partnership Project (3GPP). It supports technologies such as different MIMO schemes, adaptive coding and modulation (ACM) and hybrid automated repeat request (H-ARQ) that allow to transmit data with high spectral efficiency. LTE supports bandwidth from 1.4 MHz up to 20 MHz, corresponding to a number of data subcarriers ranging from 72 to 1200. The subcarrier spacing is fixed to 15 kHz. Depending on the cyclic prefix length, being either extended or normal, each LTE subframe consists of 12 or 14 OFDM symbols, respectively. The duration of an LTE subframe is 1 ms. The structure of the pilot symbols is described in [14].

This pilot symbol pattern allows to estimate a MIMO channel as independent SISO channels, neglecting spatial correlation. Therefore it is sufficient to consider a SISO system model. The  $n$ -th received OFDM symbol  $y_n$  at one receive antenna port can be written as

$$y_n = G_n x_n + w_n, \tag{1}$$

where the matrix  $G_n$  is the channel matrix in the frequency domain of the  $n$ -th OFDM symbol and  $w_n$  denotes additive complex white Gaussian noise with zero mean and variance  $\sigma_w^2$ . The vector  $x_n$  is comprised of data symbols  $x_{d,n}$  and pilot symbols  $x_{p,n}$

$$x_n = P [ x_{d,n}^T, x_{p,n}^T ]^T, \tag{2}$$

permuted with a permutation matrix  $P$ . The length of the vector  $x_n$  is  $K$ , corresponding to the number of subcarriers. Note that according to Equation (2), the vectors  $y_n$  and  $w_n$  can also be divided into two parts corresponding to the pilot symbol positions and to the data symbol positions.

The channel matrix of the  $n$ -th OFDM symbol in the time domain is given by

$$H_n = \begin{pmatrix} h_{n,1,0} & \cdot & 0 & \dots & \dots & \dots & \dots & 0 \\ h_{n,1,N-1} & & \cdot & & & & & \cdot \\ 0 & & \cdot & & & & & \cdot \\ \vdots & & \cdot & & & & & \cdot \\ 0 & \dots & 0 & h_{n,N_s-N_h+1,N_h-1} & \dots & h_{n,N_s,0} \end{pmatrix}, \tag{3}$$

where  $h_{n,m,\tau}$  is the channel coefficient of the  $m$ -th sample within the  $n$ -th OFDM symbol at delay  $\tau$ . The length of the channel impulse response is  $N_h$ . The time domain channel matrix  $H_n$  is transformed to the frequency domain by considering the OFDM signal structure:

$$G_n = \frac{F_{guardrem} D F_{cp}^H}{D1} H_n \frac{F_{cp} D^H F_{guard}}{D2} \tag{4}$$

The matrices  $F_{guardrem}$  and  $F_{CPrem}$  correspond to the moval of the guard subcarriers and the cyclic prefix, respectively [15]. The matrices  $F_{guard}$  and  $F_{CP}$  add guard subcarriers and the cyclic prefix, respectively. The matrix  $D$  is the DFT matrix. If the channel is not varying during the transmission of one OFDM symbol,  $G_n$  is a diagonal matrix. If the channel is varying within one OFDM symbol,  $G_n$  is not diagonal and ICI occurs.

IV. ICI ESTIMATION

The channel in the time domain can be split into two parts, one corresponding to the mean channel and one to the time variation of the channel:

$$H_n = \text{Toep}(\bar{h}_n) + \Delta H_n \tag{6}$$

Here the vector  $h_n$  comprises the mean channel impulse response as experienced by the  $n$ -th OFDM symbol. The channel in the frequency domain using this structure is given by

$$G_n = D1 [ \text{Toep}(\bar{h}_n) + \Delta H_n ] D2 \tag{7}$$

where the vector  $g_n$  contains the diagonal elements of the channel matrix in the frequency domain. The operator  $\text{diag}(b)$  creates a diagonal matrix with the vector  $b$  on the main diagonal.

III. CHANNEL ESTIMATION

In this section, we present state-of-the-art channel estimators for estimating the main diagonal elements of the channel matrix in the frequency domain. Note that, although we restrict ourselves to least squares (LS) and linear minimum mean square error (LMMSE) channel estimation here, ICI estimation method presented in the next section can be combined with any OFDM channel estimator. A typical OFDM channel estimator estimates only the main diagonal elements of the frequency domain channel matrix  $G_n$ . ICI estimator, on the other hand, estimates the remaining off-diagonal elements of the channel matrix by using the main diagonal elements of the channel matrices of the remaining OFDM symbols through interpolation.

A. LS Channel Estimation

The LS channel estimator for the pilot symbol positions is given by

$$g_p^{LS} = \underset{g_p}{\text{argmin}} \| y_p - X_p g_p \|_2^2 = X_p^{-1} y_p \tag{9}$$

where the matrix  $X_p$  is a diagonal matrix comprising pilot symbols on the main diagonal.

B. LMMSE Channel Estimation

The LMMSE channel estimator requires the knowledge of the second order statistics of the channel and the noise. It can be shown that the LMMSE channel estimate is obtained by multiplying the LS estimate with a filtering matrix  $A_{LMMSE}$

$$g^{LMMSE} = A_{LMMSE} g_p^{LS} \tag{10}$$

In this section, we generalize a method for estimating the

ICI in the frequency domain introduced in [7] to arbitrary basis functions. Furthermore, we discuss improvements that allows to increase the polynomial order and as a consequence to obtain better ICI estimates at high Doppler spreads. Furthermore, the overall complexity of the estimator is reduced. The estimated channel coefficients of one subframe are the only input to the ICI estimator. We assume that  $h_n$  is the same as the channel observed in the middle of the particular OFDM symbol. The ICI estimation algorithm can be used as add-on to any channel estimator. Here, as "channel estimator" we understand a signal processing block that estimates only the diagonal elements of the channel matrix in the frequency domain. The off-diagonal elements are calculated by the ICI estimator as explained below.

A. General ICI Estimator

The frequency domain channel matrix can be decomposed using a set of basis functions

$$G_n = \sum_{i=0}^N \text{diag}(\gamma^{(i)} D_1 T^{(i)} D_2) \tag{12}$$

where the matrices  $T^{(i)}$  are diagonal matrices comprised of the corresponding basis vectors  $t^{(i)}$  on their main diagonals. The channel estimator delivers an estimate of the diagonal elements of the channel matrix in the frequency domain, which corresponds to the mean of the channel during the transmission of one OFDM symbol. In [7] it is shown, that if the mean channel of several consecutive OFDM symbols is known, the optimal coefficient can be obtained by means of a linear regression. Using polynomials as the basis functions in (12), the coefficients of the basis expansion model (BEM) are obtained as follows

$$\begin{matrix} \gamma_n^{(0)} & \gamma_n^{(1)} & \gamma_n^{(2)} & \dots & \gamma_n^{(N_{\text{order}})} \\ = (M^{-1} M^{-1} M^{-1} \dots M^{-1} \mathbf{g}^1 \mathbf{g}^2 \dots \mathbf{g}^{N_{\text{symbol}}})^T \end{matrix} \tag{13}$$

where the matrix M contains the sampled basis function column wise. For example, for a polynomial basis the matrix M is given as

$$M = (\mathbf{1} \ m \ m^2 \ \dots \ m^{N_{\text{order}}}) \tag{14}$$

where the operator  $\cdot^i$  denotes the element-wise raise to the power of i and the vector m has the following structure

$$\mathbf{m} = \left[ \underline{N_s}, \ N_s + \underline{N_s}, \ \dots, \ N_s (N_{\text{symbol}} - 1) + \underline{N_s} \right]^T$$

with  $N_{\text{symbol}}$  being the number of OFDM symbols within one Subframe

B. Discussion

In this subsection, we will discuss the concept of the ICI estimator introduced in Section IV-A and furthermore the choice of the basis functions.

1) *Linear Case*: If we use polynomials as the basis spanning the channel space and set the variable  $N_{\text{order}} = 1$ , we assume that the channel is varying linearly in time. Higher order channel variations are not taken into account. The same assumption has been made in [4–6]. It was shown, that such an assumption is valid at low Doppler spreads.

2) *Discrete prolate spheroidal (DPS) sequences*: In [12] a low-dimensional subspace spanned by discrete prolate spheroidal sequences is used for time-variant channel estimation. The subspace is designed according to the maximum velocity  $v_{\text{max}}$  of the user. It is shown in [12] that the channel estimation bias obtained with the Slepian basis expansion is more than a magnitude smaller compared to the Fourier basis expansion (i.e. a truncated discrete Fourier transform) [20] or a polynomial. The concept introduced in [12], can be directly extended to the ICI estimation. The polynomials in (12) are replaced by DPS sequences.

V. CONCLUSION

The ICI estimation algorithm can be applied to OFDM systems with arbitrary pilot structure. Using this ICI estimate of estimator in combination with the assumption that the channel matrix in the frequency domain is a band matrix, we can achieve a large performance gain (SINR gain up to 3.7 dB) by means of a ZF receiver. In a flat Rayleigh fading scenario, a user is able to move approximately 150 km/h faster while obtaining the same throughput as if he would utilize an OFDM receiver that does not consider ICI.

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## Biography



**GAYATRI PAL**

Received BE degree in Electronics & communication Engineering from the **S.V.I.T.S.Indore**, India in 2010,

*Corresponding  
palgayatri1989@gmail.com*

*address:*