Pilot and data aided channel estimation for uplink MC-CDMA mobile systems

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Abstract- **A pilot-aided joint channel estimation and data detection method for uplink MC-CDMA mobile system is proposed. Conventional pilot-aided estimation with low pilot overhead is used to obtain an initial estimate of channel. The information bits obtained from the first iteration are subsequently used to improve channel estimates. The second iteration uses a Parallel Interference Canceller (PIC) scheme followed by a frequency-time domain Wiener filter. Results show that the proposed pilot-and-data-aided channel estimator allows, at price of some complexity increase, the use of short pilot sequences and increases the number of uplink radio channel that can be simultaneously estimated.**

I. INTRODUCTION

Multi-carrier code division multiple access (MC-CDMA) [1] has attracted significant attention as one of the most promising access techniques for Beyond 3G (B3G) mobile communication systems. This scheme combines efficiently Orthogonal Frequency Division Multiplex (OFDM) and CDMA. MC-CDMA is for example studied within the European IST-MATRICE and 4MORE projects [2][3]. A very important feature of an OFDM system is its capability to spread the signal bandwidth without increasing the adverse effect of Inter Symbol Interference (ISI). In contrast to DS-CDMA technique, MC-CDMA does not multiply the user signal by a chip sequence, but the same information bit is transmitted over multiple sub-carriers simultaneously. If the bandwidth of each sub-carrier is much less than the channel coherence bandwidth, a flat fading channel model can be assumed for each sub-carrier. Moreover, inserting a cyclic prefix results in an ISI free condition, if the length of the guard interval is greater than the delay spread of the channel. Therefore, the effect of the multi-path channel on each sub-carrier can be represented by a single complex multiplier, which changes the amplitude and phase of the transmitted symbol. Hence, the equalizer at the receiver can be implemented by a set of complex multipliers, one for each sub-carrier. Since the channel information is required by the equalization algorithm, channel estimation is a crucial part of the receiver structure.

Blind channel estimation techniques that try to estimate the channel without any knowledge of the transmitted data are only effective when a large amount of data can be collected to make a reliable stochastic estimation [4]. It is clear that blind channel estimation is disadvantageous in mobile applications, for which the time-varying channel would preclude accumulation of a large amount of data. Therefore pilot-symbol aided channel estimation is more suitable for such systems. In those channel estimators, known pilot tones are multiplexed into the transmitted data sub-carriers and channel estimation is performed by interpolation between these pilots [5]. However, for uplink, channel estimation is very challenging since it is necessary to estimate a different radio channels simultaneously, one for each active user.

This problem becomes more serious in MIMO (Multiple Input Multiple Output) systems using space-time codes, because the numbers of radio channels increases with the number of transmit antennas [6]. To overcome this problem, the use of pilot-and-data aided channel estimation schemes appears to be a suitable means to achieve good performance keeping the length of the pilot sequences a small as possible [7][8]. Nevertheless, these techniques suffer an additional problem with MC-CDMA transmission caused by presence of the Multiple Access Interference (MAI) inherent to CDMA systems.

In this work we present an iterative pilot-and-data-aided channel estimation algorithm for the uplink MC-CDMA system. In the first iteration only the pilots are used for channel estimation. Based on the Least Square (LS) algorithm, followed by a two dimensional interpolation, channel estimates are generated for all intermediate symbols. This first channel estimative is then used for the regeneration of the information bits. Once the information bits have been regenerated, they are feedback to the channel estimator, which treats them as a virtual pilot sequence. The second iteration starts to cancel the MAI using Parallel Interference Cancelator (PIC) scheme and after that, the MMSE (Minimum Mean Square Error) criterion is applied along with data symbols, to improve the accuracy of the first channel estimate.

The estimation algorithm was implemented and integrated in a link level simulation platform for the physical layer of MC-CDMA transmission [2]. Computer simulation results shows the Mean Square Error (MSE) and the BER performance improvements obtained by applying the pilot-and-data-aided channel estimation algorithm when compared against conventional pilot-based algorithm over a time variant and frequency selective channel.

The paper is organized as follows. Section 2 presents the burst structure adopted. Section 3 presents the system description. Section 4 presents a pilot and data aided channel estimation algorithm. Section 5 gives some simulation results. Finally the main conclusions of this paper are given in Section 6.

II. THE BURST STRUCTURE

The most important parameters for the selection of a pilot pattern are the expected maximum speed, which determines the minimum coherence time, and the maximum excess delay, which determines the minimum coherence bandwidth. The pilot pattern design is a trade-off between good channel estimation (closely spaced pilots) and high spectral and power efficiency (sparsely spaced pilots). As discussed in [9], the grid density of the pilot symbols must satisfy the 2-D sampling theorem in order to recover channel parameters, that is,

$$f_{d\max}\, TsD_t \le 1/2 \quad , \quad \tau_{\max}\, \Delta f D_f \le 1/2 \qquad (1)$$

where D_t denotes the time spacing in terms of MC-CDMA symbols between two pilot sub-carriers, Ts is the duration of a MC-CDMA symbol including the cyclic prefix, D_f denotes the frequency distance, which is the number of sub-carriers between two adjacent pilots, and Δf is the sub-carrier spacing. In (1) $f_{d\max}=f_c v_{\max}/c$ is the maximum Doppler frequency where c is the speed of light, $v_{\max}$ is the maximum mobile speed and f_c is the carrier frequency. $\tau_{\max}$ represents the maximum path delay of the power delay profile. For the simplicity and robustness of the channel estimator, an adjustment according to the worst-case scenario for Doppler frequency and excess delay is often suggested.

In this paper we use the parameters defined within the MATRICE project [2], for a broadband MC-CDMA communications system. According to this proposal the following parameters would be used; f_c=5 GHz, $v_{\max}$= 300 Km/h, (resulting in a maximum Doppler shift $f_{d\max}$=1.38 KHz) and RF bandwidth of 57.6 MHz. The number of sub-carriers was considered to be Nc=1024 but just 736 are available for transmission. The time between symbol samples Δ=17.4 ns. Considering that the cyclic prefix has 20% of data symbol duration, (Ts) implies $Ts=1.2Nc\Delta$=21.3 µs. Using these parameters and considering the condition in (1), we will have; TsD_t <362 µs, or $D_t \le 17$ MC-CDMA symbols. Also, for the worst-case scenario of the BRAN-E outdoor radio channel with maximum delay spread of 1760 ns [10], the frequency distance is calculated as $\Delta f D_f$ <284 KHz, or $D_f \le 5$ sub-carriers.

The frame structure used in this paper is the proposed for MATRICE project [2] with 4 pilot symbols and 24 data symbols, shown in Figure 1 The pilots time separation is a constant parameter equal to D_t=8 symbols.

For the uplink the different users multiplex their pilot sequences using a FDMA scheme, thus, the pilots frequency separation (D_f) must be equal to the number of uplink simultaneous users (K). Hence, to satisfy the sampling theorem and obtain good estimates, the maximum number of uplink users must be equal to 5. This value may be too small in practical systems. Our goal is to develop channel estimation techniques to increase the number of uplink users keeping good estimates and the same pilot overhead.

III. SYSTEM MODEL

At the transmitter side, for each user k, a stream of complex QPSK data symbols is encoded and interleaved. After that, is converted from serial-to-parallel to produce M symbols $d_{k,i}$ (i=0,…,M-1), where M denotes the number of data symbols per transmitter OFDM symbol.

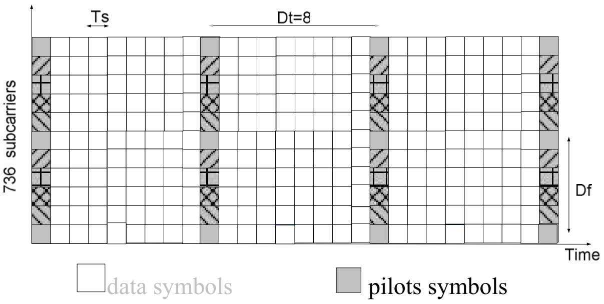

Figure 1: MC-CDMA burst structure with pilots insertion. *Df=K*

The data symbols are then spread into SF chips using the orthogonal Walsh-Hadamard code set represented as $\mathbf{c}_k=[c_{k,0},\ldots,c_{k,SF-1}]$. The element of the data spreading sequence are included into the QPSK constellation set $\{\pm 1 \pm j\}/\sqrt{2SF}$ satisfying,

$$\sum_{s=0}^{SF-1} \left| d_{k,i} c_{k,s} \right|^2 = 1, \quad \forall\, k,i \qquad (2)$$

Subsequently, M.SF chips, each responsible for modulation one of the Nc subcarriers, build one OFDM symbol using IFFT operation. After that, in order to avoid ISI, a cyclic prefix (CP) is added. Finally, the transmitted signal crosses the multipath fading channel with frequency response H_k.

A block scheme of the MC-CDMA base station receiver with pilot and data aided channel estimator is shown in Figure 2. To simplify the figure we only represent a single user detection scheme. At the receiver side, after OFDM demodulation (FFT operation), the pilots symbols are extracted from the burst structure and exploited to obtain the first estimate of the channel ($\hat{H}_k^{(1)}$). This estimate is then used in the detection of the information bits stream ($\hat{b}_k^{(1)}$), as we can see in Figure 2. Once the information bits have been detected, encoded and interleaved (represented as π), they are used to regenerate the transmitted signal, i.e., $\hat{d}_{k,i}\,.\mathbf{c}_k$, and feedback to the channel estimator, which treat them as a virtual pilot sequence. Note that the encoder and interleaving process is incorporated in feedback loop, so the error correction code improves the detection performance providing more reliable estimates $\hat{b}_k^{(1)}$ to the second iteration. Although, some of the detected $\hat{b}_k^{(1)}$ may be erroneous; however if the error probability is sufficiently low, the new channel estimate, $\hat{H}_k^{(2)}$, will expectedly be more reliable than the previous one. Now the new channel estimate feeds the MC-CDMA detector to get new estimates for information bits stream ($\hat{b}_k^{(2)}$) with an expected lower error probability. This iterative process could be repeated to improve the channel estimate accuracy at the price of complexity increase.

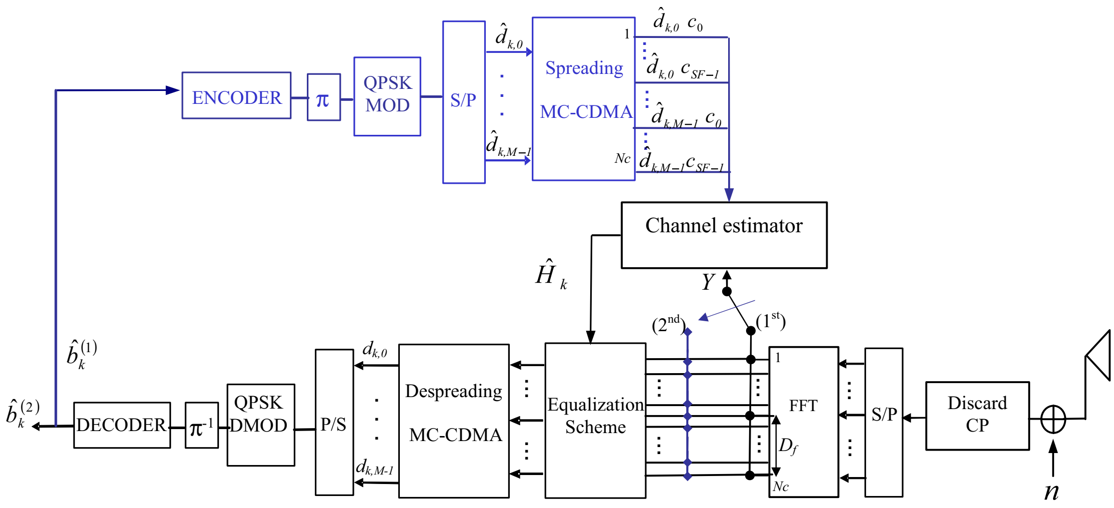

Figure 2: Receiver structure of a MC-CDMA base station system, with pilot and data aided channel estimator (single user detection).

IV. PILOT AND DATA AIDED CHANNEL ESTIMATOR

Since we are on an uplink scenario, the received signal is the sum of the contributions from all users. Then the received signal after OFDM demodulation is obtained,

$$Y = \sum_{k=0}^{K\text{-}1} X_{\mathrm{k}} H_k + n \tag{3}$$

where Y is the Ncx1 vector and X_k is the 1xNc transmitted signal vector, relatively to user k. n is a vector of independent identically distributed complex zero-mean Gaussian noise with variance σ^2_n. n is assumed to be uncorrelated with the channel H_k. In the following we assume, without loss of generality, that the variances of the channel attenuations in H_k are normalized to unit, i.e., $E[|H_k|^2]=1\ \forall k$.

A. First iteration: pilot-aided channel estimator

The initial estimate, $\hat{H}_k^{(1)}$, is obtained using the Least Square (LS) approach for the pilots positions, followed by a two dimensional interpolation operation. Using the conventional LS approach, the channel at the pilot locations is simply obtained by dividing the received signal over pilot tones with the known transmitted pilot symbols. In a matrix form this can be written as:

$$\hat{H}_{LS}^{(1)} = Xp_k^{-1} Yp_k \tag{4}$$

where Xp_k is NpxNp diagonal matrix of the transmitted pilot tones included in one OFDM pilot symbol, $Np=Nc/D_f$ and Yp_k is the received vector carriers corresponding to the pilot tones. In this paper we consider a pilot sequence constant and equal to 1, i.e, Xp_k is an identity matrix. Thus, both pilots and data symbols have the same average power.

The channel responses of data sub-carriers are obtained by interpolating the LS estimative at the pilot positions. To obtain $\hat{H}_k^{(1)}$ a second-order polynomial interpolation is applied in the frequency domain to estimate the channel at other sub-carriers. After that, a simple linear interpolation is used to obtain the time varying channel over each sub-carrier.

To illustrate the performance of the channel estimator only based on pilots, the ideal channel response and the respective channel estimate can be seen in Figure 3 and Figure 4, respectively, where an entire burst was transmitted. It was used a spacing between two adjacent pilots D_f=16 and BRAN E channel model. Once D_f>5 (BRAN E coherence bandwidth), we can see that in frequency dimension the channel estimate does not achieve to follow the rapid channel fluctuations. To overcome this problem, a second iteration is performed using the regenerated data symbols.

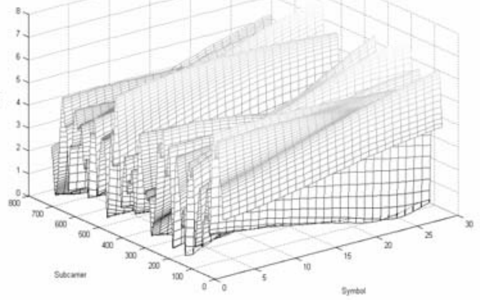

Figure 3: Ideal channel response; BRAN E, 60 Km/h and Eb/N0=10 dB.

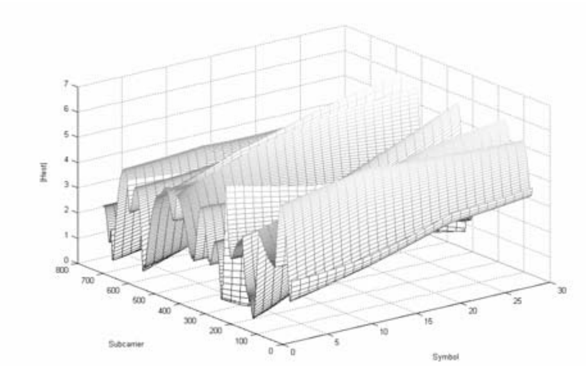

Figure 4: Channel estimate obtained with pilot-aided channel estimator, BRAN E, D_f=16, 60 Km/h and Eb/N0=10 dB.

B. Second iteration: PIC followed by data-aide channel estimator

It is known that in MC-CDMA transmission data symbols are corrupted by multiple access interference, so it is crucial to perform some interference cancellation before data-aided channel estimation. Because of its low complexity we choose a hard-decision PIC scheme. For a generic data symbol *i* the PIC for the desired user *k* can be expressed as follows:

$$\tilde{Y}_{k,i} = Y_i - \sum_{\substack{j=0 \\ j\neq k}}^{K-1} \hat{d}_{j,i}.c_j \circ \hat{H}_j^{(1)} \tag{5}$$

where (o) means element wise vector product. In (5) we assume that the frequency response of the channels is estimated through the first iteration, $\hat{H}^{(1)}$. After the PIC the second iteration applies the LS algorithm,

$$\hat{H}_{LS}^{(2)} = \hat{X}_k^{-1}\tilde{Y}_k \tag{6}$$

where $\hat{X}_k$ represents the previous estimated data signal given by *Nc*x*Nc* diagonal matrix,

$$X_k = \hat{d}_i \cdot \boldsymbol{c}_k \tag{7}$$

Conventional LS channel estimation method is very sensitive to the Gaussian noise. Notice that the signal to noise ratio (SNR) in data tones is $SNR=1/(SF\sigma_n^2)$, lower than the *SNR* in pilot tones, $SNRp=1/\sigma_n^2$. Moreover there is still some multi-user interference that is not completely cancelled by PIC. Significantly better results are obtained with the MMSE method, which exploits the channel correlation in frequency and time domain. The MMSE algorithm can be implemented as a two-dimensional (2D) frequency-time domain Wiener filter, or two cascaded, one-dimensional (2x1D) filters; which is a frequency domain followed by a time domain filter. Since the 2D approach is computationally excessive, 2x1D algorithm is more practical, and provides a good trade-off between performance and complexity [9].

In one dimensional frequency domain MMSE approach, the channel estimation can be presented as [9]:

$$\hat{H}_k^{(2)} = R_f \left(R_f + \frac{I}{SNR} \right)^{-1} \hat{H}_{LS}^{(2)} \tag{8}$$

where *I* is an *Nc*x*Nc* identity matrix and R_f is the *Nc*x*Nc* frequency-domain correlation matrix that is usually unavailable at the receiver side. To circumvent this problem we propose to previous compute the desired correlation matrix using the estimative obtained in the first iteration process,

$$R_f \approx E\left\{ \hat{H}_k^{(1)} \times \left(\hat{H}_k^{(1)}\right)^* \right\} \tag{9}$$

Where $()^*$ denotes the conjugate transpose (Hermitian). This approach is robust in the sense that it can cope with different channel statistics.

After estimating the channel for each sub-carrier into the same OFDM symbol, a similar MMSE filter is applied to exploit the channel correlation in time dimension over different sub carriers.

The major drawback of the MMSE estimator is its high computational complexity, involving matrix inversion which dimension grows with number of sub carriers. However the complexity of MMSE estimator could be reduced by using low-rank approximation and single value decomposition [10].

V. SIMULATION RESULTS

The uplink MC-CDMA system used in the simulations was introduced in Section 2 with the burst structure proposed in Section 1. The following table shows the main parameters of the MC-CDMA simulation chain,

Table 1: Parameters of the simulated uplink MC-CDMA system.

RF bandwidth	57.6 MHz
Carrier frequency	5 GHz
Number of FFT points	1024
Available subcarriers	736
Number of uplink users	16 (full load)
Spreading factor	16
Radio Channel	BRAN E, 60 Km/h [10]
Coding	Turbo code (UMTS like)
Equalization	MRC
Modulation	QPSK

In order to evaluate the performance of the proposed uplink channel estimation algorithm, the normalized mean square error (*MSE*) was analysed,

$$MSE = 10\log\left(\mathrm{E}\left[\left| \frac{H-\hat{H}}{H} \right|^2 \right] \right) \tag{10}$$

Figure 5 shows the *MSE* for conventional pilot-aided estimator (i.e., 1st iteration) versus the proposed pilot-and-data-aided channel estimator. It is seen that there is an irreducible error floor for pilot-aided *MSE* curve with D_f=16, due an high interpolation error. In fact, for BRAN E channel model and pilots separation D_f=16 the Nyquist criterion is not satisfied (see Section II). The pilot-and-data-aided channel estimator with D_f=16, achieves almost the same *MSE* that would be achieved with the conventional pilot-aided channel estimator with, D_f=8, i.e. twice the number of pilots. In other words, with the same overhead we can estimate twice more channels, keeping a similar estimation error.

For the pilot-and-data-aided estimator, the *MSE* depends on the bit error probability, with which the information bits have been detected on the first iteration (BER(1st)). Figure 5 represents too the performance for pilot-and-data-aided estimator if BER(1st)=0, which is a lower bound theoretical limit. The *MSE* obtained with pilot-and-data-aided algorithm converge to that limit when Eb/N0=6 dB. Notice that for Eb/N0=6 dB the bits on first iteration have been detected with a not-so-small error probability, i.e. BER(1st)=8x10^{-2}, see 1st iteration curve in Figure 6. Than, it is enough to have BER(1st)<8x10^{-2} to assure the maximum channel estimator performance.

Figure 6 shows BER performance degradation due to channel estimation inaccuracy, for hard-detector PIC in full load scenario, *K*=16. When detector PIC uses a simple pilot-aided channel estimator (only 1st iteration), the BER became similar than the obtained with conventional single user detector, i.e., with an irreducible BER floor. This low performance is due to the poor channel estimation accuracy (*MSE*>-6 dB in Figure 5). However, with pilot-and-data-aided channel estimator the PIC performance became close to the lower bound limit, obtained with perfect channel knowledge. The performance degradation for BER=1x10^{-3} is about 2 dB.

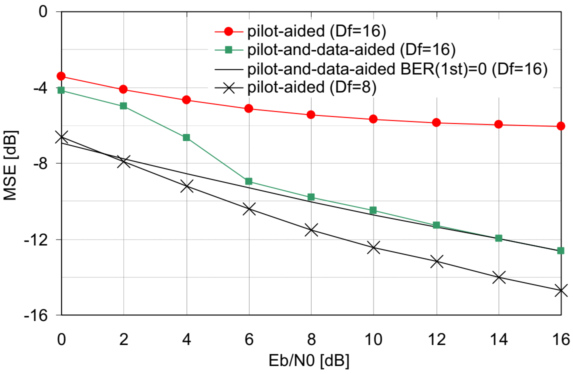

Figure 5: Channel estimation MSE for conventional pilot-aided vs. pilot-and-data-aided channel estimators.

VI. CONCLUSIONS

In this paper, we have considered the problem of joint channel estimation and data detection in MC-CDMA uplink mobile systems. A two-iteration algorithm was proposed, whose basic idea is to recursively exploit the information detected bits in order to improve the first channel estimate obtained with pilots only. Simulation result shows that the proposed pilot-and-data-aided channel estimator allows to increase the number of uplink radio channel that can be simultaneously estimated, keeping similar channel estimation accuracy.

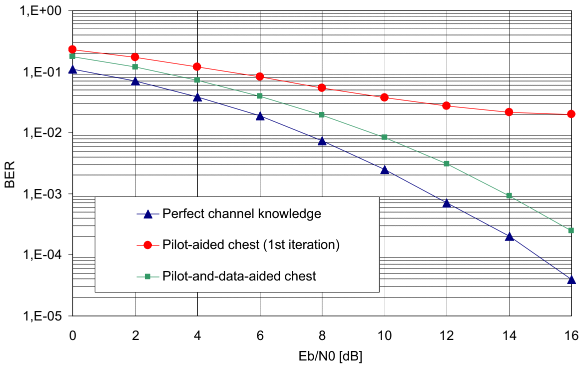

Figure 6: Effect of channel estimation algorithm on hard detector-PIC performance. Full load scenario (*K*=D_f=16).

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