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Channel Estimation for IFDMA – Comparison of Semiblind Channel Estimation Approaches and Estimation with Interpolation Filtering

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***Abstract*—In this paper, Discrete Fourier Transform (DFT) precoded Orthogonal Frequency Division Multiple Access (OFDMA) with interleaved subcarrier allocation per user is considered which is denoted as Interleaved Frequency Division Multiple Access (IFDMA). In order to estimate the channel for IFDMA, in general, each subcarrier of an IFDMA symbol is used for pilot transmission to fulfill the sampling theorem in frequency domain. If the data of different users is additionally separated by a time division multiple access component, a limited number K of successive IFDMA symbols is transmitted and at least two of these K symbols are used for pilot transmission if the channel is estimated with the help of interpolation filters. In this paper, we propose to estimate the channel with an iterative decision directed channel estimation with Wiener filtering in order to reduce the pilot symbol overhead in time domain. We additionally introduce the combination of this approach with semiblind subspace based channel estimation in order to reduce the pilot symbol overhead in frequency domain. By this means the channel can be estimated even if the sampling theorem is not fulfilled. The new approach outperforms the iterative decision directed channel estimation with Least-Squares estimation on each subcarrier and the Wiener interpolation filter for Signal-to-Noise Ratios larger than 20 dB and for velocities up to 15 km/h.**

I. Introduction

At present, Orthogonal Frequency Division Multiple Access (OFDMA) is under discussion as one of the candidate multiple access schemes for future mobile radio systems. Other promising multiple access schemes result from the application of Discrete Fourier Transform (DFT) precoding to OFDMA which helps to combine most of the advantages of OFDMA with a low Peak-to-Average Power Ratio (PAPR) of the transmit signal [1]. In this work, the focus is on DFT-precoded OFDMA with interleaved subcarrier allocation resulting in the well known Interleaved Frequency Division Multiple Access (IFDMA) scheme [2], [3].

The IFDMA signal generation can be described in Time Domain (TD) as a compression, repetition and subsequent user dependent phase rotation of blocks of modulated data symbols giving rise to a very efficient implementation for signal generation in TD [2]. Furthermore, compared to other DFT-precoded OFDMA schemes, IFDMA provides the lowest PAPR enabling the application of low cost amplifiers [4]. IFDMA supports an additional user separation via a Time Division Multiple Access (TDMA) component. I.e., during one TDMA frame, each user is assigned to a specific set of K successive IFDMA symbols. For each user terminal, this opens up the possibility to enter a micro sleep mode during the transmission phase of the other users and to achieve considerable energy savings if K is small compared to the interval between consecutive TDMA frames [5].

In Frequency Domain (FD), the IFDMA signal of each user is transmitted on a user specific set of Q subcarriers that are equidistantly distributed over the available bandwidth. In general, the distance between adjacent subcarriers allocated to a user is larger than the coherence bandwidth of the channel. On the one hand, this leads to high frequency diversity of the IFDMA signal, but on the other hand, in terms of pilot assisted Channel Estimation (CE), each allocated subcarrier has to be used for pilot transmission to fulfill the sampling theorem in FD [6].

The CE for IFDMA can be realized by a cascaded two times one-dimensional (2x1D) filtering process in FD and TD. In FD, the channel can be estimated with the help of pilot symbols transmitted on each allocated subcarrier. In TD, the channel can be estimated by the application of a Wiener Interpolation Filter if there are at least two pilot carrying IFDMA symbols within the K successively transmitted symbols in TD. Thus, the pilot symbol overhead increases if less successive symbols are transmitted in TD. In order to reduce the pilot symbol overhead for transmission within a limited number K of successive symbols, we propose to apply a decision directed CE in TD which avoids the need of a second pilot carrying symbol in TD.

In [7] and [8], decision directed CE has been presented for IFDMA. For both approaches, the initializing channel estimate that is required for decision directed estimation is obtained by the transmission of pilot symbols on each allocated subcarrier in FD. In [9], decision directed CE is proposed for the general case of single carrier systems. A 2x1D Wiener interpolation filter is applied to obtain the initializing estimate as well as to refine the final decision directed channel estimate. For IFDMA, the application of interpolation filters in FD fails due to the distributed subcarriers. Nevertheless, the reduction of pilot symbols in FD as well as the refinement of the decision directed estimate is desirable. Therefore, in this paper, we propose to combine Semiblind Subspace based CE with a decision directed CE in order to reduce the pilot symbol overhead in TD. By this means, the channel can be estimated even if the sampling theorem in FD is not fulfilled and current

CE approaches fail. In order to mitigate error propagation in TD, we propose to apply an iterative Wiener filter to the decision directed estimates in TD, i.e. the filtered channel estimates are iteratively reused in the decision directed CE which improves the estimation performance compared to current decision directed CE approaches. Numerical results are presented comparing the performance of the new iterative Decision Directed Channel Estimation with Wiener Filtering (DDCE+WF) with Semiblind initialization, the iterative DDCE+WF with an Least-Squares (LS) initialization for each allocated subcarrier and the well-known Wiener Interpolation Filtering in TD.

The rest of the paper is organized as follows. In Section II, the IFDMA system model is described. In Section III, CE is explained for IFDMA. The well-known Wiener Interpolation Filter is given and the iterative DDCE+WF with LS initialization and with Semiblind initialization is introduced. In Section IV, numerical results illustrating the differences between the algorithms are discussed. Section V concludes the work.

II. IFDMA System Model

In this section, a system model for IFDMA will be derived in TD. In the following, all signals are represented by their discrete time equivalents in the complex baseband. Vectors in TD and FD are denoted by lower and upper case boldfaced letters, respectively. Further on, $(\cdot)^*$, $(\cdot)^{\mathrm{T}}$, $(\cdot)^{\mathrm{H}}$ and $\mathrm{E}\{\cdot\}$ denote the conjugate complex, the transpose, the Hermitian and the expectation of a vector or a matrix. A diagonal matrix having the vector $\mathbf{a}$ as its main diagonal is represented by diag$\{\mathbf{a}\}$.

Assuming a system with U users, let

$$\mathbf{d}^{(u)}(i) = [d_0^{(u)}(i), \cdots, d_{Q-1}^{(u)}(i)]^{\mathrm{T}} \tag{1}$$

denote the ith block, $i = 1, \cdots, K$, of Q data symbols $d_q^{(u)}(i)$, $q = 0, \cdots, Q-1$, transmitted at symbol rate $1/T_s$ by a user with index u, $u = 0, \cdots, U-1$. The data symbols $d_q^{(u)}(i)$ can be taken from the alphabet of a modulation scheme like Phase Shift Keying or Quadrature Amplitude Modulation and are assumed to be i.i.d. with zero-mean. An IFDMA symbol is obtained by L_u-fold compression of the block $\mathbf{d}^{(u)}(i)$, with $L_u = C/Q$ and C the number of available subcarriers in the system. The block of compressed data symbols is denoted by $\mathbf{w}^{(u)}(i) = [w_0^{(u)}(i), \cdots, w_{Q-1}^{(u)}(i)]$ with $\mathrm{E}\{|w_q^{(u)}(i)|^2\} = \sigma_w^2$. Subsequently, $\mathbf{w}^{(u)}(i)$ is repeated L_u-times. In order to avoid inter-block and inter-carrier interference, each IFDMA symbol is preceded by a Cyclic Prefix (CP) that corresponds to an L_g-fold repetition of the compressed block with $(L_g \cdot Q) \in \mathbb{Z}$ [2]. The vector of $L = (L_u + L_g)$-times repeated blocks is multiplied by a user dependent phase shift matrix $\mathcal{J}^{(u)} = \mathrm{diag}(\exp\{-j \cdot 0 \cdot \varphi^{(u)}\}, \exp\{-j \cdot 1 \cdot \varphi^{(u)}\}, \cdots, \exp\{-j \cdot (LQ-1) \cdot \varphi^{(u)}\})$, with $\varphi^{(u)} = u \cdot 2\pi/C$. Thus, the resulting ith IFDMA symbol of user u including CP is given by

$$\mathbf{x}^{(u)}(i) \quad = \quad \mathcal{J}^{(u)} \cdot \underbrace{[\mathbf{w}^{(u)}(i), \cdots, \mathbf{w}^{(u)}(i)]^{\mathrm{T}}}_{L-\text{times}} . \tag{2}$$

This modulation leads to the characteristic IFDMA subcarrier allocation in FD, where the elements $\mathbf{D}^{(u)}(i) = [D_0^{(u)}(i), \cdots, D_{Q-1}^{(u)}(i)]^{\mathrm{T}}$ of the DFT of the data block $\mathbf{d}^{(u)}(i)$ are transmitted on Q equidistantly distributed subcarriers with a spacing of L_u/T_s.

The IFDMA signal $\mathbf{x}^{(u)}(i)$ is transmitted over a channel with impulse response $\mathbf{h}^{(u)}(i)$ and M non-zero coefficients $h_m^{(u)}(i)$, $m = 0, \cdots, M-1$, at chip rate. The channel is assumed to be time-invariant during the transmission of one IFDMA symbol and the transmission over this multipath channel can be described by a flat fading channel for each allocated subcarrier in FD. With $H_q^{(u)}(i)$ denoting the complex channel coefficient, $D_q^{(u)}(i)$ the DFT of the transmitted data symbols and $V_q^{(u)}(i)$ the Additive White Gaussian Noise (AWGN) on the subcarrier with index q and the symbol with index i, the received values on each subcarrier in FD can be described by

$$R_q^{(u)}(i) = H_q^{(u)}(i) \cdot D_q^{(u)}(i) + V_q^{(u)}(i) \, , \quad q = 0, \cdots, Q-1 \, . \tag{3}$$

III. Channel Estimation

In the following, different channel estimation approaches with different pilot symbol overhead are described for IFDMA. The proposed new iterative DDCE+WF with Semiblind initialization is introduced as an approach to reduce the pilot symbol overhead in FD. In the sequel, the user index u is omitted.

In order to estimate the channel at the receiver, K_p symbols with index $\iota = 0, \cdots, K_p - 1$ are used to transmit pilot symbols on a subset consisting of Q_p out of Q subcarriers in FD [6]. An estimate of the channel transfer factor of the pilot carrying subcarrier with index $\kappa = 0, \cdots, Q_p - 1$ in the corresponding IFDMA symbol with index ι is determined by an LS estimation and, thus, given by

$$\hat{H}_\kappa(\iota) = \frac{R_\kappa(\iota)}{P_\kappa(\iota)} \, , \tag{4}$$

with $P_\kappa(\iota)$ the pilot symbol transmitted on the κ-th pilot carrying subcarrier in the ι-th pilot carrying IFDMA symbol. The LS-estimates $\hat{\mathbf{H}}_{\text{LS}}(\iota) = [\hat{H}_0(\iota), \cdots, \hat{H}_{Q_p-1}(\iota)]$ are exploited to estimate the channel transfer factors of the remaining, non-pilot carrying subcarriers and symbols. The channel estimation can be seen as a two times 1-dimensional channel estimation process in FD and TD and, thus, can be divided in the estimation approach in FD and the estimation approach in TD.

In general, for IFDMA, the application of interpolation filters in FD is not possible as the distance between neighboring subcarriers is large compared to the coherence bandwidth of the channel. Thus, channel estimation approaches in FD that are known up to now involve the usage of each allocated subcarrier for pilot transmission, i.e. $Q_p = Q$.

For channel estimation in TD, two approaches are given in the following. The first one is the well-known Wiener Interpolation Filter that is applicable if there are at least two pilot carrying symbols in TD, i.e. $K_p \geq 2$, as it is shown in Figure 1(a). The second one is an iterative DDCE+WF that is feasible if there is only one pilot carrying symbol in TD, i.e.

$K_p = 1$ [10]. On the one hand, the iterative DDCE+WF can be initialized by LS estimation for each allocated subcarrier in the first IFDMA-symbol, cf. Figure 1(b). On the other hand, due to the iterative nature of the DDCE+WF, the propagation of estimation errors in FD can be mitigated during estimation in TD. Thus, we propose to initialize the iterative DDCE+WF approach with a Semiblind Subspace based CE, that allows to estimate the channel in FD with $Q_p < Q$ pilot subcarriers, cf. Figure 1(c), although the sampling theorem is not fulfilled and known interpolation filters fail in this case.

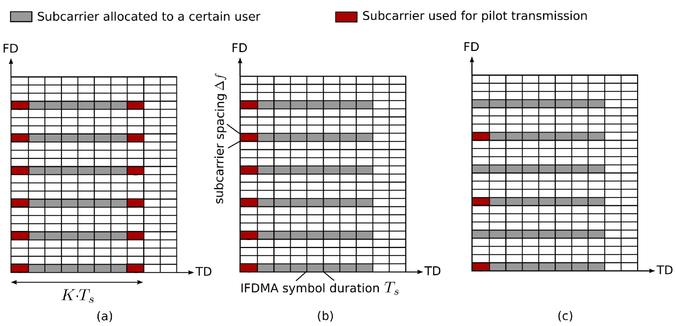


Fig. 1. Exemplary subcarrier allocation for IFDMA with pilot arrangements for (a) Wiener Interpolation Filtering, (b) iterative DDCE+WF and initialization with LS on each subcarrier, (c) iterative DDCE+WF and initialization with Semiblind Subspace based CE.

A. *Wiener Interpolation Filter*

The Wiener Interpolation Filter can be applied if there is an LS estimate of each allocated subcarrier, i.e. $\hat{\mathbf{H}}_{\mathrm{LS}}(\iota) = [\hat{H}_0(\iota), \cdots, \hat{H}_{Q-1}(\iota)]$, available for at least two IFDMA symbols in TD, i.e. $K_p \geq 2$. With $c_{\iota,i}$ the Wiener filter coefficients determined to minimize $\mathrm{E}\{|\mathbf{H}(i) - \tilde{\mathbf{H}}(i)|^2\}$, the channel estimate for the non-pilot carrying symbols in TD is then given by

$$\tilde{\mathbf{H}}(i) = \sum_{\iota=1}^{K_p} c_{\iota,i} \cdot \hat{\mathbf{H}}_{\mathrm{LS}}(\iota) \,. \tag{5}$$

B. *Iterative DDCE + Wiener Filtering*

For the application of the iterative DDCE+WF only one pilot carrying IFDMA symbol is required in TD ($K_p = 1$) and, thus, the iterative DDCE+WF is feasible with less pilot symbols than the Wiener Interpolation Filter.

1) Initialization with LS on each subcarrier: The iterative DDCE+WF can be initialized with an LS estimate of each allocated subcarrier in the first IFDMA symbol, i.e. $\hat{\mathbf{H}}_{\mathrm{LS}}(\iota = 0) = [\hat{H}_0(0), \cdots, \hat{H}_{Q-1}(0)]$. This initial channel estimation is exploited to start the DDCE in the IFDMA symbol with index $i = 1$. Afterwards a Wiener filter is applied to the decision directed estimates and the filtered estimates are used iteratively for DDCE again. In Table I, the basic method of the iterative DDCE+WF is outlined according to [10].

2) Initialization with Semiblind Subspace Based CE: In order to reduce the number of pilot symbols that are used for the initializing estimate of the iterative DDCE+WF, we propose to initialize the iterative DDCE+WF with a Semiblind Subspace based CE. For this, $Q_p < Q$ subcarriers of the first IFDMA symbol are used to transmit pilot symbols. The LS estimates of the Q_p pilot carrying subcarriers are combined with a Subspace based CE approach, as the application of interpolation filters in FD fails.

TABLE I
ITERATIVE DDCE+WF WITH LS INITIALIZATION

1. DDCE Initialization **(a)** Equalization with LS estimate of first symbol, i.e. $\hat{\mathbf{H}}_{\mathrm{LS}}(0)$ Estimation of transmitted symbols $\rightarrow \hat{\mathbf{D}}(1)$ **(b)** First Decision Directed Channel Estimation $\hat{\mathbf{H}}_{\mathrm{DDE}}(1) = \mathbf{R}(1)/\hat{\mathbf{D}}(1)$ **(c)** Wiener Filtering with two coefficients b_0, b_1 $\tilde{\mathbf{H}}(1) = b_1 \cdot \hat{\mathbf{H}}_{\mathrm{LS}}(0) + b_0 \cdot \hat{\mathbf{H}}_{\mathrm{DDE}}(1)$
For $i = 1, \ldots, K-1$
2. Equalization with $\tilde{\mathbf{H}}(i)$ Estimation of transmitted symbols $\rightarrow \hat{\mathbf{D}}(i+1)$
3. Decision Directed Channel Estimation $\hat{\mathbf{H}}_{\mathrm{DDE}}(i+1) = \mathbf{R}(i+1)/\hat{\mathbf{D}}(i+1)$
4. Wiener Filtering with a maximum of S filter coefficients $b_0, \ldots, b_{S-1}$ $\tilde{\mathbf{H}}(i+1) = \sum_{s=1}^{S-1} b_s \cdot \tilde{\mathbf{H}}(i+1-s) + b_0 \cdot \hat{\mathbf{H}}_{\mathrm{DDE}}(i+1)$

In the following, this initializing Semiblind Subspace based CE is explained and the integration of this estimate into the iterative DDCE+WF is elaborated.

Let the ith IFDMA symbol $\mathbf{r}(i) = [r_0(i), \cdots, r_{L \cdot Q-1}(i)]$ that is received after transmission over the channel with impulse response $\mathbf{h}(i)$ be split into L blocks with Q elements, i.e. $\mathbf{r}(i) = [\mathbf{r}_0(i), \cdots, \mathbf{r}_{L-1}(i)]^{\mathrm{T}}$ due to the L-fold repetition of the compressed data blocks at the transmitter. Now, three adjacent blocks of length Q of the received signal in TD are considered. The vector $\mathbf{r}_s(i) = [\mathbf{r}_{L-1}(i-1), \mathbf{r}_0(i), \mathbf{r}_1(i)]^{\mathrm{T}}$ containing the last block $\mathbf{r}_{L-1}(i-1)$ of the IFDMA symbol with index $i-1$ and the first two blocks $\mathbf{r}_0(i)$ and $\mathbf{r}_1(i)$ of the IFDMA symbol with index i is exploited to calculate an estimate for the autocorrelation matrix $\mathcal{A} = \mathrm{E}\{\mathbf{r}_s(i) \cdot \mathbf{r}_s(i)^{\mathrm{H}}\}$ of $\mathbf{r}_s(i)$ by the arithmetic mean over K IFDMA symbols given by

$$\hat{\mathcal{A}} = \frac{1}{K} \sum_{i=0}^{K-1} \mathbf{r}_s(i) \cdot \mathbf{r}_s(i)^{\mathrm{H}} \,. \tag{6}$$

In [11] it has been shown that $3 \cdot Q$ received elements in $\mathbf{r}_s(i)$ are dependent on $2 \cdot Q$ transmit symbols due to the redundancy in the transmit signal. Thus, the channel can be estimated by separating $\hat{\mathcal{A}}$ into the signal and the noise subspace via an Eigenvalue Decomposition (EVD) of $\hat{\mathcal{A}}$ [12].

The EVD of $\hat{\mathcal{A}}$ leads to the estimates $\hat{\mathbf{g}}_0, \cdots, \hat{\mathbf{g}}_{Q-1}$ of the Q noise subspace eigenvectors of $\hat{\mathcal{A}}$. The noise subspace eigenvectors $\hat{\mathbf{g}}_n$ can be transformed into the matrices $\hat{\mathcal{G}}_n$, $n = 0, ..., Q-1$. Due to orthogonality between signal and noise subspace, the channel can be estimated up to a scalar ambiguity by minimizing $\sum_{n=0}^{Q-1} \parallel \mathbf{h}^{\mathrm{H}} \cdot \hat{\mathcal{G}}_n \parallel^2$ for $\mathbf{h}$ [11].

To resolve this scalar ambiguity, the minimization problem is combined with the LS estimates $\hat{\mathbf{H}}_{\mathrm{LS}}(0) =$

$[\hat{H}_0(0), \cdots, \hat{H}_{Q_p-1}(0)]$ of the channel transfer factor of $Q_p < Q$ subcarriers in the first IFDMA symbol in the following system of equations as it has been proposed in [12]:

$$\left\{ \begin{array}{lcll} \mathbf{h}^{\mathrm{H}} \cdot \mathcal{G}_n & = & \mathbf{0} & 0 \leq n \leq Q-1 \\ \mathcal{F} \cdot \mathbf{h} & = & \hat{\mathbf{H}}_{\mathrm{LS}}(0) & \end{array} \right. , \quad (7)$$

with $\mathcal{F}$ the $Q_p \times M$ matrix given by the M first columns and the Q_p rows representing the pilot positions of a Q-point DFT matrix.

Solving this system of equations for $\mathbf{h}$ leads to the estimate $\hat{\mathbf{h}}_{\mathrm{semi}}$ of the channel that is given by

$$\hat{\mathbf{h}}_{\mathrm{semi}} = \left(\sum_{n=0}^{Q-1} \hat{\mathcal{G}}_n \cdot \hat{\mathcal{G}}_n^{\mathrm{H}} + \mathcal{F}^{\mathrm{H}} \cdot \mathcal{F} \right)^{-1} \cdot \mathcal{F}^{\mathrm{H}} \cdot \hat{\mathbf{H}}_{\mathrm{LS}} . \quad (8)$$

As the estimate $\hat{\mathbf{h}}_{\mathrm{semi}}$ is based on the arithmetic mean in (6), it represents a joint estimate for the time indices $i = 0, \cdots, K-1$. Therefore, the estimation performance of $\hat{\mathbf{h}}_{\mathrm{semi}}$ is hardly differing for the different IFDMA symbols with index i. During DDCE, one can benefit from the evenly distributed estimation performance in TD by considering S neighboring symbols jointly as it is outlined in Table II.

TABLE II
ITERATIVE DDCE+WF WITH SEMIBLIND INITIALIZATION

1. DDCE Initialization
Equalization with the Fourier transform $\hat{\mathbf{H}}_{\mathrm{semi}}$ of the Semiblind Subspace based CE $\hat{\mathbf{h}}_{\mathrm{semi}}$
Estimation of transmitted symbols $\rightarrow \hat{\mathbf{D}}^{(0)}(1), \cdots, \hat{\mathbf{D}}^{(0)}(S)$

For $i = 1, \ldots, K-1$

2. Decision Directed Channel Estimation
$\hat{\mathbf{H}}_{\mathrm{DDE}}^{(i)}(i) = \frac{\mathbf{R}(i)}{\hat{\mathbf{D}}^{(i-1)}(i)}, \cdots, \hat{\mathbf{H}}_{\mathrm{DDE}}^{(i)}(e_1) = \frac{\mathbf{R}(e_1)}{\hat{\mathbf{D}}^{(i-1)}(e_1)}$

$$e_1 = \left\{ \begin{array}{ll} S & \text{for } i \leq S/2 \\ K-1 & \text{for } i > K - S/2 - 1 \\ i + S/2 - 1 & \text{else} \end{array} \right.$$

3. Wiener Filtering with S filter coefficients
$\tilde{\mathbf{H}}(i) = \sum_{s=e_2}^{0} b_s \cdot \hat{\mathbf{H}}_{\mathrm{DDE}}^{(i)}(i-s) + \sum_{s=1}^{e_3} b_s \cdot \tilde{\mathbf{H}}(i-s)$

$$e_2 = \left\{ \begin{array}{l} i - S \\ i + 1 - K \\ -S/2 + 1 \end{array} \right. \quad e_3 = \left\{ \begin{array}{ll} i-1 & \text{for } i \leq S/2 \\ S - K + i & \text{for } i > K - S/2 - 1 \\ S/2 & \text{else} \end{array} \right.$$

4. Equalization with $\tilde{\mathbf{H}}(i)$
Estimation of transmitted symbols $\rightarrow \hat{\mathbf{D}}^{(i)}(i+1), \cdots, \hat{\mathbf{D}}^{(i)}(e_1)$

IV. PERFORMANCE ANALYSIS

In this section, the performance of the three considered channel estimation approaches is investigated for velocities of $v = 5$ km/h, $v = 10$ km/h, $v = 15$ km/h and $v = 20$ km/h, respectively. Fig. 2 and 3 present the channel estimation performances for Wiener Interpolation Filtering, iterative DDCE+WF with LS initialization and iterative DDCE+WF with Semiblind initialization. As a performance measure the Mean Square Error (MSE) between the estimated and the true channel transfer function, i.e. MSE $= \sum_{i=0}^{K-1} \|\tilde{\mathbf{H}}(i) - \mathbf{H}(i)\|^2 / (Q \cdot K)$, is chosen as a result of 500 channel realizations. The MSE is depicted in dependency of the Signal-to-Noise Ratio (SNR) E_s/N_0, i.e. energy per symbol over noise power. The results are valid for a Rayleigh fading channel with an exponential power delay profile and for the parameters given in Table III. The presented results already include the differing pilot symbol overhead for the particular estimation approach as an SNR degradation [13]. Further on, the filter length S of the iterative DDCE+WF is chosen as $S = 8$ and it is assumed that the channel correlations in TD are known to the Wiener filters.

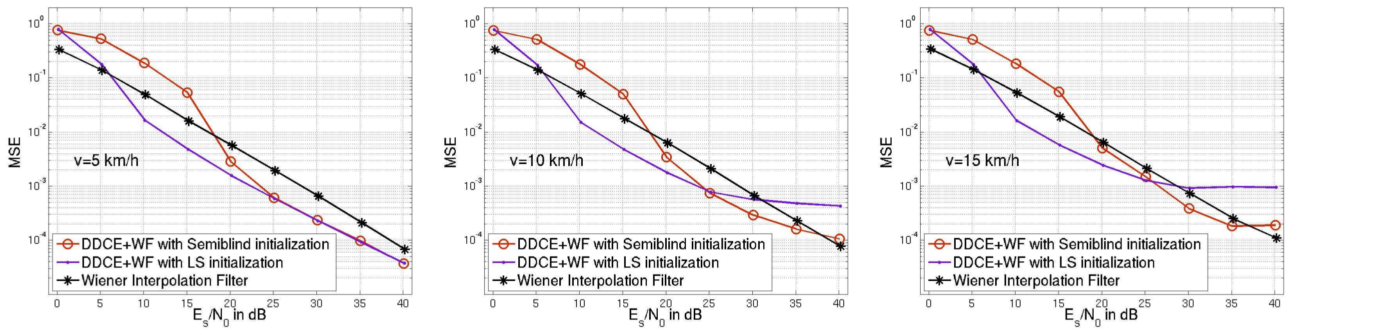
TABLE III
SIMULATION PARAMETERS

Carrier Frequency	3.7 GHz
Bandwidth	40 MHz
Total No. of Subcarriers	1024
Subcarrier Spacing Δf	39.1 kHz
No. Q of Subcarriers per user	8
No. K of successive IFDMA symbols	30
Guard Interval	3.2 μs
Coherence bandwidth	$B_{\mathrm{coh}} = 128 \cdot \Delta f$

In Fig. 2(a), results are presented for $v = 5$ km/h. It can be seen that the iterative DDCE+WF with LS initialization outperforms the Wiener Interpolation Filter for SNR values larger than 6 dB, because the iterative DDCE+WF is able to mitigate the estimation error caused by the LS estimation in FD. The maximum improvement is about 6 dB for $E_s/N_0 = 18$ dB. Considering the MSE for DDCE+WF with Semiblind initialization, it can be seen that it shows only poor performance for low SNR values but clearly outperforms the MSE of the Wiener Interpolation Filter up to 6 dB for $E_s/N_0 > 18$ dB. For $E_s/N_0 > 25$ dB, the iterative DDCE+WF with Semiblind and LS initialization show the same performance. This is due to the Semiblind initialization, which is best for high SNR values.

In Fig. 2(b), results are presented for the same parameters as in Fig. 2(a) but for $v = 10$ km/h. The performance of each estimation approach is very similar to the performance shown in Fig. 2(a). The effect of the increasing velocity can be seen for high SNR values, where the performance of the iterative DDCE+WF with LS initialization degrades to the performance of the Wiener Interpolation Filter for $E_s/N_0 = 30$ dB and finally runs into an error floor. The MSE of the iterative DDCE+WF with Semiblind initialization also degrades due to the higher velocity, but still outperforms the performance of LS initialization for $E_s/N_0 \geq 25$ dB.

In Fig. 2(c) and Fig. 3, i.e. for $v = 15$ km/h and $v = 20$ km/h, the mentioned effect is even increased and the MSE of the iterative DDCE+WF with Semiblind and LS initialization exhibit increasing error floors, respectively. The error floor of the MSE for LS initialization occurs for lower SNR-values than the error floor for Semiblind initialization. The reason for that is the performance of the Semiblind Subspace based initializing estimate that shows an MSE that hardly differs for the $K = 30$ IFDMA symbols. The DDCE takes advantage of the performance that is evenly distributed in time and evaluates $S = 8$ neighboring symbols jointly.



(a) (b) (c)

Fig. 2. Comparison of DDCE+WF with Semiblind Initialization, DDCE+WF with LS Initialization and Wiener Interpolation Filter for (a) $v = 5$ km/h, (b) $v = 10$ km/h and (c) $v = 15$ km/h.

From simulation results that are not presented due to limited space, it came out that the lower the number K of successive IFDMA symbols the more can be gained by the iterative DDCE+WF compared to conventional Wiener Interpolation Filtering. Nevertheless, the iterative DDCE+WF with Semiblind initialization requires a certain number of symbols as it is based on the arithmetic mean in (6). Thus, for $K \leq 20$ it is feasible to apply the iterative DDCE+WF with LS initialization which can also cope with higher velocities for a small number K of successively transmitted symbols. On the other hand, with Semiblind initialization, the distance between neighboring pilot carrying subcarriers can be extended to two times the coherence bandwidth, whereas with conventional filtering in FD a pilot symbol has to be transmitted within the fifth-part of the coherence bandwidth, i.e. on each allocated subcarrier for IFDMA [6].

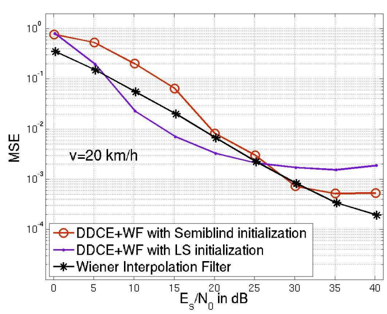


Fig. 3. Comparison of DDCE+WF with Semiblind Initialization, DDCE+WF with LS Initialization and Wiener Interpolation Filter for $v = 20$ km/h.

V. Conclusion

For IFDMA, the iterative DDCE+WF with Semiblind initialization is introduced which allows to estimate the channel with a reduced number of pilot symbols even if the sampling theorem in TD and FD is not fulfilled. It is compared to the iterative DDCE+WF with LS initialization and to Wiener Interpolation Filtering. It came out, that for low to high SNR regions, the iterative DDCE+WF with LS initialization shows performance advantages compared to Wiener Interpolation Filters and iterative DDCE+WF with Semiblind initialization. The Semiblind initialization approach shows best performances for very high SNR-regions which is due to the nature of Subspace based estimation approaches. Due to the combination of Semiblind Subspace based estimation and iterative DDCE+WF, the performance of Semiblind estimation for moderate SNR regions can be clearly improved and channel estimation with a pilot distance in FD that violates the sampling theorem is possible. Nevertheless, conventional estimation approaches with pilot distances in FD that fulfill the sampling theorem still outperform iterative DDCE+WF with Semiblind initialization for moderate SNR regions.

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