BLOCK-IFDMA – ITERATIVE CHANNEL ESTIMATION VERSUS ESTIMATION WITH INTERPOLATION FILTERS

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Abstract In this paper, Discrete Fourier Transform (DFT) precoded Orthogonal Frequency Division Multiple Access (OFDM) with block-interleaved subcarrier allocation per user is considered which is denoted as Block Interleaved Frequency Division Multiple Access (B-IFDMA). The B-IFDMA parameter design is affected on the one hand by considerations to reduce the energy consumption by entering a micro sleep mode. These considerations recommend a transmission on a high number of subcarriers and a small number of successive symbols. On the other hand, in terms of channel estimation, an increasing number of successive symbols is beneficial to reduce the pilot symbol overhead. The paper contributes to the choice of the B-IFDMA system parameters, i.e., blocksize in frequency domain and number of successive symbols in time domain, that are investigated in consideration of channel estimation performance and pilot symbol overhead. Further on, a novel iterative Decision Directed Channel Estimation with Wiener filtering is proposed that requires only one pilot carrying B-IFDMA symbol in time domain and, thus, reduces the pilot symbol overhead especially if a small number of successive symbols is transmitted. In this paper, this novel channel estimation algorithm is introduced and compared to Wiener interpolation filtering and additionally to a low-complexity channel estimation approach.

1. Introduction

Within the ongoing research activities of future mobile radio systems, Discrete Fourier Transform (DFT) precoded Orthogonal Frequency Division Multiple Access (OFDMA) is a candidate multiple access scheme for non-adaptive transmission.
For DFT precoded OFDMA, there exist different possibilities of allocating subcarriers to a certain user. In this paper, Block Interleaved Fre-

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quency Division Multiple Access (B-IFDMA) is considered, where the data symbols of a specific user are transmitted on several blocks of K_f adjacent subcarriers that are equidistantly distributed over the available bandwidth. B-IFDMA is a generalization of the well-known Interleaved Frequency Division Multiple Access (IFDMA), where a block consists of a single subcarrier [1, 2]. Due to the blockwise subcarrier allocation, B-IFDMA exhibits higher robustness against carrier frequency offsets than IFDMA and, at the same time, maintains the advantage of high frequency diversity [3]. In terms of Pilot Assisted Channel Estimation (PACE), interpolation in Frequency Domain (FD) is applicable for B-IFDMA within each block of K_f adjacent subcarriers. Thus, B-IFDMA benefits from a lower pilot symbol overhead compared to IFDMA if the distance between neighboring blocks is larger than the coherence bandwidth [4].

Furthermore, B-IFDMA supports an additional user separation via a Time Division Multiple Access (TDMA) component. I.e., during one TDMA slot, each user is assigned to a specific set of K_t successive B-IFDMA symbols. For each user, this opens up the possibility to enter a micro sleep mode and to achieve considerable energy savings if K_t is small compared to the interval between consecutive TDMA slots [3]. Thus, it is desirable to achieve a certain data rate by the transmission of a small number of successive B-IFDMA symbols and the allocation of a high number of subcarriers to each user [3].

On the other hand, considering PACE, the application of interpolation filters in Time Domain (TD) and FD, which is a favorable technique to estimate the channel for the non-pilot carrying symbols and subcarriers, involves the usage of at least two B-IFDMA symbols within the K_t successive symbols in TD and at least two subcarriers within each block of K_f subcarriers in FD for pilot transmission. Hence, in TD the pilot symbol overhead increases if less successive symbols are transmitted and a TDMA slot with a high number of successive B-IFDMA symbols that are assigned to a user would be beneficial. In FD, interpolation filtering is only possible if there are more than two subcarriers per block ($K_f > 2$).

In order to reduce the pilot symbol overhead for transmission with a small number K_t of successive symbols assigned to a user, we propose a novel iterative Decision Directed Channel Estimation with Wiener filtering (iterative DDCE+WF) in TD for B-IFDMA which avoids the need of a second pilot carrying symbol in TD while achieving estimation performances comparable to Wiener interpolation.

In this paper, the novel iterative DDCE+WF is compared with a conventional Wiener interpolation filter and with an alternative approach requiring only one pilot carrying B-IFDMA symbol. The optimal choice of the B-IFDMA system parameters, i.e., number K_f of subcarriers per block and number K_t of successive symbols, is investigated in consideration of channel estimation performance and pilot symbol overhead.

2. System Model

In this section, a system model for B-IFDMA will be derived. In the following, all signals are represented by their discrete time equivalents in the complex baseband. Further on, $(\cdot)^{\mathrm{T}}$ denotes the transpose and $(\cdot)^{\mathrm{H}}$ the Hermitian of a vector or a matrix. Assuming a system with U users, the data symbols transmitted by a user with index u at symbol rate $1/T_s$ are grouped into a vector $\mathbf{d}^{(u)}(i) = (d_0^{(u)}(i), \ldots, d_{Q-1}^{(u)}(i))^{\mathrm{T}}$ with index i, $i = 0, \ldots, K_t - 1$, denoting the index of the B-IFDMA symbol. 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, that is applied to coded or uncoded bits. Let $\mathbf{F}_N$ and $\mathbf{F}_N^{\mathrm{H}}$ denote the matrix representation of an N-point DFT and an N-point Inverse DFT (IDFT) matrix, respectively, where $N = U \cdot Q$ is the number of available subcarriers in the system. The assignment of the data symbols $d_q^{(u)}(i)$ to the user specific set of Q subcarriers can be described by a Q-point DFT precoding matrix $\mathbf{F}_Q$, an $N \times Q$ mapping matrix $\mathbf{M}^{(k)}$ and an N-point IDFT matrix $\mathbf{F}_N^{\mathrm{H}}$ [5]. The mapping matrix $\mathbf{M}^{(u)}$ has to describe the allocation of Q/K_f blocks each consisting of K_f adjacent subcarriers to the user with index u. $\mathbf{M}^{(u)}$ is given by its elements $M^{(u)}(n, q)$ in the n-th row and q-th column as

$$M^{(u)}(n, q = r + s \cdot K_f) = \begin{cases} 1 & n = s \cdot \frac{NK_f}{Q} + r + u \cdot K_f \\ 0 & \text{else} \end{cases}, \tag{1}$$

with $n = 0, \cdots, N-1$, $r = 0, ..., K_f - 1$, and $s = 0, ..., Q/K_f - 1$. Thus, the resulting ith, $i = 0, \cdots, K_t - 1$, B-IFDMA symbol of user u at chip rate $1/T_c = U/T_S$ is given by

$$\mathbf{x}^{(u)}(i) = \mathbf{F}_N^{\mathrm{H}} \cdot \mathbf{M}^{(u)} \cdot \mathbf{F}_Q \cdot \mathbf{d}^{(u)}(i). \tag{2}$$

In order to avoid intersymbol and inter-carrier interference, a Cyclic Prefix is inserted in-between successive B-IFDMA symbols. The resulting B-IFDMA signal is transmitted over a channel with impulse response $\mathbf{h}^{(u)}(i)$ and $L < Q$ non-zero coefficients $h_l^{(u)}(i), l = 0, \cdots, L-1$, at chip rate. The channel is assumed to be time-invariant during the transmission of one B-IFDMA symbol and the transmission over this multipath channel can be described by a flat fading channel for each allocated subcarrier in FD. With $H_q(i)$ denoting the complex channel coefficient, $D_q(i)$ the DFT of the transmitted data symbols and $V_q(i)$ 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

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

3. Channel Estimation

In the following, different appropriate methods of channel estimation in FD and TD are described for B-IFDMA. The proposed new iterative DDCE+WF is introduced as an approach to estimate the channel in TD iteratively. For simplicity and without loss of generality, the user index u is omitted in the sequel.
In order to estimate the channel at the receiver, P_t symbols with index $\iota = 0, \cdots, P_t-1$ are used to transmit pilot symbols on a subset consisting of P_f out of Q subcarriers in FD [4]. An estimate of the channel transfer factor of the pilot carrying subcarrier with index $\kappa = 0, \cdots, P_f - 1$ in the corresponding B-IFDMA symbol with index ι is determined by a Least-Squares (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 B-IFDMA symbol. The LS-estimates $\hat{\mathbf{H}}(\iota) = [\hat{H}_0(\iota), \cdots, \hat{H}_{P_f-1}(\iota)]$ are exploited to estimate the channel transfer factors of the remaining, non-pilot carrying subcarriers and symbols. First, the estimation is performed in FD and then used to estimate the channel in TD. Depending on the block size K_f in FD and the number K_t of successive B-IFDMA symbols, different pilot arrangements and, thus, different channel estimation approaches are applicable. In Fig. 1, the B-IFDMA signal is given in TD and FD for exemplary sets of parameters and various pilot arrangements.

3.1 Frequency Domain

Wiener Interpolation Filter. For the application of the well-known Wiener Interpolation Filter in FD at least two subcarriers within each block of K_f subcarriers are used for pilot transmission, cf. Fig. 1(a), (b). In general, the distance between neighboring blocks is larger than the coherence bandwidth and, thus, interpolation is only possible within each block of subcarriers. I.e., an estimate of the channel transfer coefficients of the non pilot-carrying subcarriers within each block can be

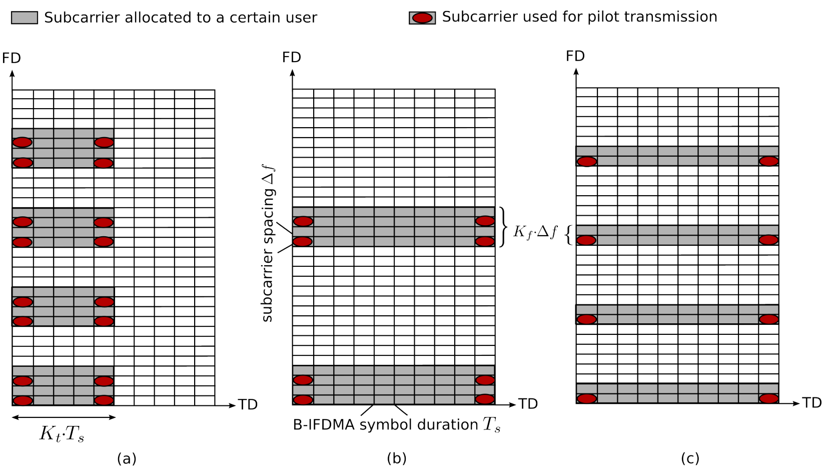

Figure 1. Exemplary subcarrier allocations and pilot arrangements for B-IFDMA (a) $K_t = 5$, $Q = 16$, $K_f = 4$ (b) $K_t = 10$, $Q = 8$, $K_f = 4$, (c) $K_t = 10$, $Q = 8$, $K_f = 2$.

obtained by filtering with a Wiener filter according to [6]. With $b_{\kappa,q}$ the Wiener filter coefficients determined to minimize $\mathrm{E}\{|H_q(\iota) - \tilde{H}_q(\iota)|^2\}$, the channel estimate in FD is given by

$$\tilde{H}_q(\iota) = \sum_{\kappa=1}^{P_f K_f / Q} b_{\kappa,q} \cdot \hat{H}_\kappa(\iota) \, . \tag{5}$$

Repetition. For the application of Repetition in FD only one pilot symbol is required within each block of K_f subcarriers in FD, as it is depicted in Fig. 1(c). The channel variations are assumed to be negligible within a certain fraction of the coherence bandwidth and the LS-estimate of the nearest pilot carrying subcarrier is used for equalization. Thus, the vector $\tilde{\mathbf{H}}(\iota)$ containing the channel estimates for each allocated subcarrier is given by

$$\tilde{\mathbf{H}}(\iota) = [\underbrace{\hat{H}_{\kappa=1}(\iota), \hat{H}_{\kappa=1}(\iota), \cdots}_{K_f\text{-times}}, \cdots, \underbrace{\hat{H}_{\kappa=P_f-1}(\iota), \hat{H}_{\kappa=P_f-1}(\iota)}_{K_f\text{-times}}] \, . \tag{6}$$

Subcarrierwise Least-Squares. For Subcarrierwise LS in FD each allocated subcarrier is used for pilot transmission, i.e. $P_f = Q$, and the channel transfer factors $\hat{H}_\kappa(\iota)$, $\kappa = 0, \cdots, Q-1$, of the allocated subcarriers are determined by LS-estimation, i.e. $\hat{H}_\kappa(\iota) = \frac{R_\kappa(\iota)}{P_\kappa(\iota)}$ and $\tilde{\mathbf{H}}(\iota) = [\hat{H}_0(\iota), \cdots, \hat{H}_{Q-1}(\iota)]$. In this paper, the LS estimation on each subcarrier is included to provide a reference compared to the channel estimation approaches with reduced number of pilot symbols.

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3.2 Time Domain

Wiener Interpolation Filter. For the application of Wiener Interpolation Filter in TD at least two pilot carrying B-IFDMA symbols, i.e. $P_t \geq 2$, are required in TD as it is shown in Figure 1. In this paper, the first and the last B-IFDMA symbol are chosen to transmit pilot symbols. With $c_{\iota,i}$ the Wiener filter coefficients determined to minimize $\mathrm{E}\{|\mathbf{H}(i) - \tilde{\mathcal{H}}(i)|^2\}$, the channel estimate in TD is given by

$$\tilde{\mathcal{H}}(i) = \sum_{\iota=1}^{P_t} b_{\iota,i} \cdot \tilde{\mathbf{H}}(\iota) \; . \tag{7}$$

Iterative DDCE + Wiener Filtering. For the application of the proposed new iterative DDCE+WF only one pilot carrying B-IFDMA symbol is required in TD and, thus, the iterative DDCE+WF is feasible where the application of Wiener Interpolation Filtering fails. In Table 1, the basic method of the iterative DDCE+WF is outlined. It is applied in TD after the channel transfer factors have been determined for each subcarrier (e.g. of the first symbol) via Repetition or Wiener interpolation. For B-IFDMA, the DDCE principle described in [7] leads to a high noise amplification with increasing number K_t of B-IFDMA symbols. Therefore, we propose a new algorithm where a Wiener filter is applied to the decision directed estimates and the filtered estimates are used iteratively for DDCE again.

Table 1. Iterative DDCE + Wiener Filter

1. Initializing Estimates
- **(a)** Wiener Interpolation Filtering / Repetition of $\hat{\mathbf{H}}(0)$ in FD $\rightarrow \tilde{\mathbf{H}}(0)$
- **(b)** Equalization with $\tilde{\mathbf{H}}(0)$
  Estimation of transmitted symbols $\rightarrow \hat{\mathbf{D}}(1)$
- **(c)** $\tilde{\mathbf{H}}(1) = \mathbf{R}(1)/\hat{\mathbf{D}}(1)$
- **(d)** Wiener Filtering of $[\tilde{\mathbf{H}}(0)\,\tilde{\mathbf{H}}(1)] \rightarrow \tilde{\mathcal{H}}(1)$

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

2. Equalization with $\tilde{\mathcal{H}}(i)$
Estimation of transmitted symbols $\rightarrow \hat{\mathbf{D}}(i+1)$

3. Decision Directed Channel Estimation
$\tilde{\mathbf{H}}(i+1) = \mathbf{R}(i+1)/\hat{\mathbf{D}}(i+1)$

4. Wiener Filtering
Wiener Filtering of $[\tilde{\mathcal{H}}(i)\,\tilde{\mathbf{H}}(i+1)] \rightarrow \tilde{\mathcal{H}}(i+1)$

Repetition. Repetition is the alternative approach to iterative DDCE + WF and requires only one pilot symbol, i.e. $P_t = 1$, within the K_t B-IFDMA symbols in TD. Here, the channel variations are assumed to be negligible within a certain fraction of the coherence time and the LS-estimate $\tilde{\mathbf{H}}(\iota)$ of the pilot carrying symbol is used for equalization of the non-pilot carrying symbols, i.e. $\tilde{\mathcal{H}}(i) = \tilde{\mathbf{H}}(\iota)$ for $i = 0, \cdots, K_t - 1$.

4. Performance Analysis

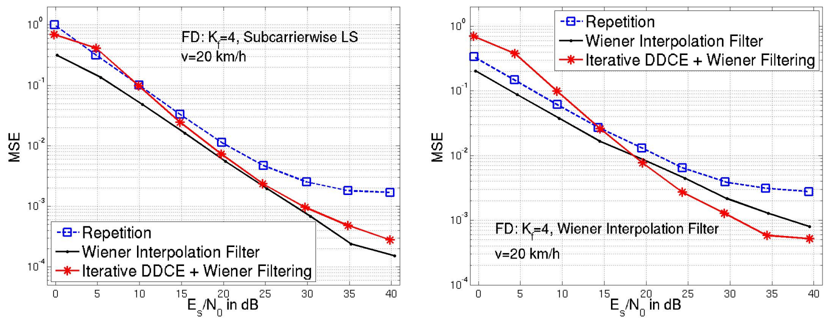
In this section, the performance of different combinations of channel estimation approaches in TD and FD are investigated for velocities of $v = 20$ km/h and $v = 50$ km/h, respectively. Fig. 2 and Fig. 3 show the Mean Square Error (MSE) between the estimated and the true channel transfer function, i.e. $\text{MSE} = \sum_{i=0}^{K_t-1} \|\tilde{\mathcal{H}}(i) - \mathbf{H}(i)\|^2/(Q \cdot K_t)$, 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, and for the parameters given in Table 2. The presented results already include the differing pilot symbol overhead for the particular estimation approach as an SNR degradation [8]. Further on, the results are valid for the assumption that the channel correlations in TD and FD are known to the Wiener Filters.

Table 2. 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	16
No. K_t of successive B-IFDMA symbols	10
Guard Interval	3.2 μs
Channel	WINNER SCM, Urban Macro
Coherence bandwidth	$B_{\text{coh}} < 20 \cdot \Delta f$

In Fig. 2(a), results are presented for $K_f = 4$ and subcarrierwise LS channel estimation in FD, i.e. the Q allocated subcarriers in the pilot carrying symbol are used for pilot transmission. In TD, the channel is estimated with a Wiener Interpolation Filter, Repetition and iterative DDCE+WF at a velocity of $v = 20$ km/h. The iterative DDCE+WF clearly outperforms the channel estimation with Repetition for SNR> 15 dB and reaches the performance of the Wiener Interpolation Filter for SNR-values between 15 dB and 30 dB.

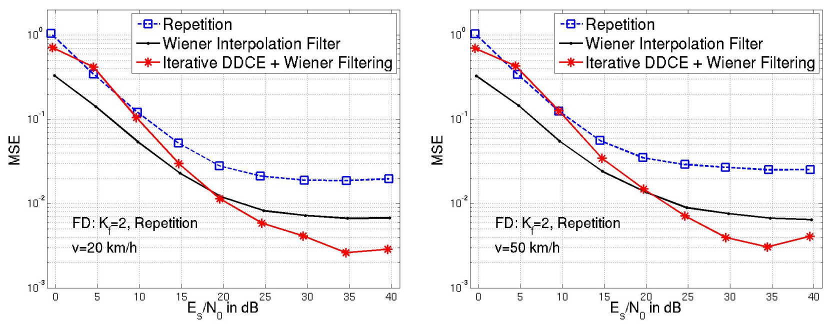
In Fig. 2(b), results are presented for the same parameters as in Fig. 2(a) but for channel estimation with a Wiener Interpolation Filter in FD. I.e., only two subcarriers out of a block consisting of $K_f = 4$ subcarriers are used for pilot transmission, cf. Fig. 1(b). It can be seen that the



(a) (b)

Figure 2. Comparison of Repetition, Wiener Interpolation Filter and iterative DDCE + Wiener Filtering in TD for (a) Subcarrierwise LS estimation in FD and $v = 20\,\text{km/h}$, (b) Wiener Interpolation Filter in FD and $v = 20\,\text{km/h}$.

performance of the Wiener Interpolation Filter and Repetition in TD is degraded for SNR>15dB as a result of the reduced number of pilot symbols in FD. The interpolation error that is caused in FD is propagated by the Wiener Interpolation Filter and Repetition in TD. In contrast, the iterative DDCE+WF shows only slight performance degradations compared to the result in Fig. 2(a). Due to symbol detection, updating channel estimation and subsequent Wiener Filtering in each iteration for iterative DDCE+WF, the propagation of the interpolation error in FD is mitigated and can be nearly avoided for a velocity of $v = 20\,\text{km/h}$.
Fig. 3 shows the MSE for the case that each block in FD consists of $K_f = 2$ subcarriers and only one subcarrier per block is used for pilot transmission, cf. Fig. 1(c). As there is only one pilot symbol available



(a) (b)

Figure 3. Comparison of Repetition, Wiener Interpolation Filter and iterative DDCE + Wiener Filtering in TD for (a) interpolation with Repetition in FD for $v = 20\,\text{km/h}$, (c) interpolation with Repetition in FD for $v = 50\,\text{km/h}$.

within the coherence bandwidth, the channel is estimated by Repetition in FD.
In Fig. 3(a), the results are presented for $v = 20\,\text{km/h}$. It shows that the performance of all three estimation approaches in TD is strongly degraded due to the inaccurate channel estimation in FD and exhibits an error floor for high SNR-values. Nevertheless, the performance of the iterative DDCE+WF is least affected in comparison to Wiener Interpolation and Repetition and, thus, outperforms even the Wiener Interpolation Filter for SNR> 18 dB.
Fig. 3(b) shows the same results for $v = 50\,\text{km/h}$. It can be seen, that the performance of the Wiener Interpolation Filter and iterative DDCE+WF is hardly affected by the increasing velocity and only the performance of Repetition in TD suffers from a higher error floor.

4.1 Parameter Selection for B-IFDMA

The results presented in Fig. 2 and Fig. 3 show that for the proposed channel estimation approaches, the performance of the estimation in FD strongly influences the overall estimation performance. Dependent on the choice of the channel estimation approach in FD and, thus, dependent on the coherence bandwidth and blocksize K_f in FD, the application of Wiener Interpolation Filter, Repetition or iterative DDCE+WF in TD lead to different estimation performances. In Table 3, an overview is given for reasonable choices of channel estimation approaches in FD and TD in dependency of the coherence bandwidth, the coherence time and the B-IFDMA parameters K_f and K_t. Table 3 is deduced from simulation results that are not shown in this paper due to limited space. In the following, K_{coh} denotes the number of B-IFDMA symbols that can be transmitted within the coherence time $T_{\text{coh}} = \frac{8.1 \cdot 10^{-2}}{v \text{ in m/s}}$ m. Wiener denotes the Wiener Interpolation Filter and DDCE denotes the iterative DDCE+WF.

Table 3. Parameter Selection

<table>
<tr><td rowspan="2">FD</td><td colspan="6">$2^{\beta-1} \cdot 10 \cdot \Delta f \leq B_{\text{coh}} < 2^{\beta} \cdot 10 \cdot \Delta f, \quad (\beta=1,2,3,4,\dots)$</td></tr>
<tr><td colspan="3">$K_f \leq 2^{\beta}$
Repetition</td><td colspan="3">$K_f > 2^{\beta}$
Wiener</td></tr>
<tr><td rowspan="3">TD</td><td colspan="2">$K_t < \frac{K_{\text{coh}}}{12}$</td><td>$K_t \geq \frac{K_{\text{coh}}}{12}$</td><td colspan="2">$K_t < \frac{K_{\text{coh}}}{17}$</td><td>$K_t \geq \frac{K_{\text{coh}}}{17}$</td></tr>
<tr><td>SNR≥ 20 dB</td><td>else</td><td rowspan="2">Wiener</td><td>SNR≥ 18 dB</td><td>else</td><td rowspan="2">Wiener</td></tr>
<tr><td>DDCE</td><td>Wiener</td><td>DDCE</td><td>Wiener</td></tr>
</table>

5. Conclusion

In this paper, different channel estimation approaches in FD and TD and their various combinations have been investigated for the case that the data symbols of a user are transmitted on K_t successive B-IFDMA symbols. A new iterative DDCE+WF that requires only one pilot carrying B-IFDMA symbol in TD has been introduced and compared to the Wiener Interpolation Filter. It came out that the performance of iterative DDCE+WF is even better than performance of the Wiener Interpolation Filter for certain parameters. The iterative DDCE+WF is preferable to Wiener Interpolation Filtering if the channel estimation performance in FD is poor. For a channel estimation in FD that suffers from interpolation errors and velocities up to $v = 70\,\text{km/h}$ it is feasible to transmit within a small number K_t of consecutive symbols compared to the coherence time and use iterative DDCE+WF. The better the channel estimation performance in FD and the higher the velocity, the better is the performance for Wiener Interpolation especially for high SNR-values.

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