Frequency-Domain Data-Aided Channel Estimation for KSP-OFDM

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***Abstract*— In this paper, we propose a new low-complexity data-aided channel estimation algorithm for known symbol padding (KSP) OFDM. Besides the pilot symbols in the guard interval, additional pilots are put on some of the OFDM carriers. The received time-domain samples are first converted to the frequency domain, and the channel estimation is based on the observation of the pilot carriers only. The proposed estimator is compared to the subset estimator from [1]. Although performing slightly worse than the subset estimator at low SNR, the proposed estimator outperforms the subset estimator at high SNR, as the former does not suffer from an error floor in the MSE. The MSE resulting from the proposed estimator is inversely proportional to the number of pilot carriers and is independent of the FFT size, the pilot carrier positions and the used pilot sequence.**

I. Introduction

Multicarrier communication (MC) [2] has become very popular because of its ability to cope with channel dispersion, making MC communication suitable for high data rate applications. To avoid intersymbol interference between successively transmitted MC blocks, a guard interval is inserted between the MC blocks. In the literature, several types of guard intervals can be found.

The most popular guard interval type is the cyclic prefix (CP) [3], where the last samples of each MC block are copied and added in front of the MC block. Another guard interval technique is zero-padding (ZP) [3], where during the guard interval no signal is transmitted. In these two guard interval techniques, maximum-likelihood (ML) channel estimation from pilot carriers is trivial and equalization can be performed in the frequency domain with low complexity. However, a disadvantage of these two guard interval techniques is the ambiguity problem that occurs in low-complexity timing synchronizers such as the Schmidl & Cox [4] algorithm.

In the third guard interval technique, i.e. known symbol padding (KSP) [5], the guard interval consists of known pilot samples. By properly selecting the pilot samples, the ambiguity problem in timing synchronization as for CP-OFDM and ZP-OFDM can be avoided [6]. As the samples of the guard interval are known, they can be used for data-aided channel estimation. However, the guard interval length is typically selected to be only slightly larger than the channel impulse response length. Hence, usually extra pilots must be inserted in the transmitted MC signal in order to improve the channel estimation accuracy. In this paper, we assume that the number of pilot samples in the guard interval is not increased, but rather the additional pilots are inserted on carriers.

In [1], [7], [8], it is shown that channel estimation in KSP-OFDM is harder than in CP-OFDM and ZP-OFDM. ML channel estimation in KSP-OFDM is very complex and suboptimal estimation techniques must be used. In [7], a suboptimal ML-based channel estimation algorithm is proposed. However, [7] assumes that the autocorrelation matrix of the disturbance (containing contributions from the noise, the data symbols and the channel) is known. Hence, before this channel estimator can be used, first the autocorrelation matrix must be estimated from the received signal. Further, even if the autocorrelation matrix is perfectly known, the resulting mean squared error (MSE) shows an error floor at high SNR, indicating that the presence of the unknown data symbols disturbs the channel estimation. In [1], the effect of the data symbols on the channel estimation is reduced by applying a linear transform to the observed time-domain samples; the resulting observations can be split into a part that depends on the data symbols and a part that is (nearly) independent of the data symbols. In the subset estimator from [1], only the latter subset of observations is used to estimate the channel. Although performing better than the estimator from [7], the subset estimator also shows an error floor at high SNR because of the residual interference from the data symbols.

In this paper, we propose a new low-complexity estimator operating in the frequency domain, which only exploits the information from the pilot carriers; the information from the guard interval pilots is discarded as they are disturbed by the data symbols. Because of the orthogonality of the carriers, the pilot carriers are not disturbed by the data symbols, so that an error floor in the MSE performance is avoided. However, as compared to the estimators from [1] and [7] the proposed algorithm performs slightly worse performance at low and intermediate SNR.

II. System Description

We consider a KSP-OFDM system with N carriers and a guard interval length ν, as shown in figure 1. The guard interval (dark gray area in figure 1) consists of ν known pilot samples. The N symbols transmitted on the carriers during the i-th OFDM block are denoted $\mathbf{a}_i = (a_i(0), \ldots, a_i(N-1))^T$. These symbols consist of $M-\nu$ pilot symbols and $N-M+\nu$ information-carrying data symbols. The $N+\nu$ time-domain

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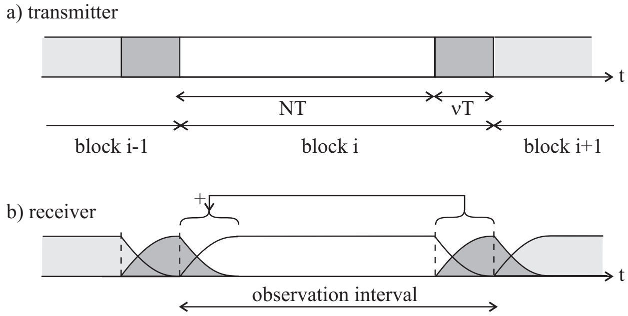

Fig. 1. Time-domain signal of KSP-OFDM a) transmitted signal b) received signal and observation interval.

samples during block i are then given by

$$\mathbf{s}_i = \sqrt{\frac{N}{N+\nu}} \begin{pmatrix} \mathbf{F}^{+}\mathbf{a}_i \\ \mathbf{b}_g \end{pmatrix}. \quad (1)$$

In (1), $\mathbf{F}$ is the $N \times N$ matrix corresponding to the FFT operation, with $\mathbf{F}_{k,\ell} = \frac{1}{\sqrt{N}} e^{-j2\pi\frac{k\ell}{N}}$, and $\mathbf{b}_g = (b_g(0), \ldots, b_g(\nu-1))^T$ are the ν known samples of the guard interval.

The KSP-OFDM signal is transmitted over a dispersive channel with L taps; the channel impulse response is given by the vector $\mathbf{h} = (h(0), \ldots, h(L-1))^T$. We select $\nu \geq L-1$ in order to avoid interference between successively transmitted OFDM symbols. Further, the signal is disturbed by additive white Gaussian noise $\mathbf{w}$, of which the statistically independent components $w(k)$ have zero mean and variance N_0. Without loss of generality, we restrict our attention to the detection of the OFDM block with index $i = 0$, and we drop the block index for notational convenience. Considering the observation interval shown in figure 1b, we can write the received $N+\nu$ time-domain samples as

$$\mathbf{r} = \mathbf{H}_{ch}\mathbf{s} + \mathbf{w} \quad (2)$$

where $(\mathbf{H}_{ch})_{k,k'} = h(k-k'-i(N+\nu))$ is the $(N+\nu)\times(N+\nu)$ channel matrix.

For data detection, the contribution from the guard interval pilots must first be subtracted from the received signal. Then, the last ν samples from the observation interval, which now contain only a data component as the contribution from the guard interval pilots is removed, are added to the first ν samples of the OFDM symbol, and the resulting samples are applied to an FFT. Note however that the guard interval pilots are affected by the channel; hence, before their contribution can be subtracted from from the received signal, the channel has to be estimated first.

III. Channel Estimation

In this section, we consider data-aided channel estimation. To estimate the channel, we assume M pilots are inserted in the transmitted signal: ν of them are the pilot samples of the guard interval, and the remaining pilots are put on $M-\nu$ OFDM carriers. We denote the $M-\nu$ pilots transmitted on the carriers as $\mathbf{b}_c = (b_c(0), \ldots, b_c(M-\nu-1))^T$. Hence, the block of symbols $\mathbf{a}$ in (1) consists of $M-\nu$ pilot symbols $\mathbf{b}_c$ and $N+\nu-M$ data symbols $\mathbf{a}_d$. We define the sets I_p and I_d as the sets of carriers modulated by pilots and data, respectively, where $I_p \cup I_d = \{0, \ldots, N-1\}$. We assume that the data symbols are independent identically distributed (i.i.d.) and have energy per symbol $E[|a_d(n)|^2] = E_s$. Further, we assume that $E[|b_c(n)|^2] = E[|b_g(m)|^2] = E_s$. The normalization factor $\sqrt{N/(N+\nu)}$ in (1) implies that $E[|s(m)|^2] = E_s$.

To estimate the channel, we consider the observation interval shown in figure 1b. Taking into account the channel vector $\mathbf{h}$ to be estimated, we rewrite (2) as

$$\mathbf{r} = \mathbf{B}\mathbf{h} + \tilde{\mathbf{w}}. \quad (3)$$

In (3), the $(N+\nu) \times L$ matrix $\mathbf{B}$ contains the contributions from the pilot symbols. It can be split into the contribution from the guard interval pilots and the pilot carriers: $\mathbf{B} = \mathbf{B}_g + \mathbf{B}_c$. The matrix $\mathbf{B}_c$ contains the contributions from the pilot carriers and is given by

$$(\mathbf{B}_c)_{k,\ell} = \sqrt{\frac{N}{N+\nu}} s_p(k-\ell). \quad (4)$$

In (4), the vector $\mathbf{s}_p$ equals the N-point IFFT of the pilot carriers only, i.e. $\mathbf{s}_p = \mathbf{F}_p\mathbf{b}_c$, where the $N \times (M-\nu)$ matrix $\mathbf{F}_p$ consists of a subset of columns of the IFFT matrix $\mathbf{F}^{+}$ corresponding to the set I_p of pilot carriers. Note that $s_p(k) = 0$ for $k < 0$ or $k \geq N$. The contribution $\mathbf{B}_g$ from the guard interval pilots is given by

$$(\mathbf{B}_g)_{k,\ell} = \sqrt{\frac{N}{N+\nu}} b_g(|k-\ell+\nu|_{N+\nu}) \quad (5)$$

where $|x|_K$ is the modulo-K operation of x yielding a result in the interval $[0, K[$, and $b_g(k) = 0$ for $k \geq \nu$. Further, the disturbance in (3) contains the contributions from the data symbols and the additive white Gaussian noise and is given by

$$\tilde{\mathbf{w}} = \mathbf{H}\mathbf{F}_d\mathbf{a}_d + \mathbf{w} \quad (6)$$

where $\mathbf{H}_{k,\ell} = h(k-\ell)$ is a $(N+\nu) \times N$ matrix, $\mathbf{F}_d$ is a $N \times (N+\nu-M)$ matrix that consists of the subset of columns of $\mathbf{F}^{+}$ corresponding to the set I_d of data carriers, and $\mathbf{a}_d$ is the vector of $N+\nu-M$ data symbols transmitted during the observed OFDM block. Hence, the contribution $\mathbf{s}_d = \mathbf{F}_d\mathbf{a}_d$ equals the N-point IFFT of the data carriers only.

A. The Subset Estimator

First, we briefly describe the subset estimator derived in [1]. In the derivation of the subset estimator, the Toeplitz matrix $\mathbf{H}$ in (6) is approximated by a circulant matrix, i.e. the transients at the edges of the observed block in the contribution from the data symbols $\mathbf{a}_d$ to the observation $\mathbf{r}$ are neglected; this approximation is valid for long blocks, i.e. $N \gg \nu$. This approximation yields $\mathbf{H}\mathbf{F}_d = \tilde{\mathbf{F}}\tilde{\mathbf{H}}$ where $\tilde{\mathbf{F}}_{k,\ell} = \frac{1}{\sqrt{N}} e^{j2\pi\frac{kn_\ell}{N}}$, $\tilde{\mathbf{H}} = diag(H_{n_\ell})$, $n_\ell \in I_d$ and

$$H_m = \sum_{k=0}^{N-1} h(k) e^{-j2\pi\frac{km}{N}}. \quad (7)$$

The QR-decomposition of the matrix $\tilde{\mathbf{F}}$, i.e. $\tilde{\mathbf{F}} = \mathbf{QV}$ where $\mathbf{Q}$ is a $(N+\nu)\times(N+\nu)$ unitary matrix ($\mathbf{Q}^+ = \mathbf{Q}^{-1}$) and

$$\mathbf{V} = \begin{pmatrix} \mathbf{U} \\ \mathbf{0} \end{pmatrix} \tag{8}$$

with $\mathbf{U}$ an upper triangular matrix and $\mathbf{0}$ the all-zero matrix, yields an invertible transform matrix $\mathbf{Q}^+$ that is independent of the channel vector to be estimated. The transform matrix converts the observation $\mathbf{r}$ into the vector $\mathbf{r}' = (\mathbf{r}_1^T \quad \mathbf{r}_2^T)^T = \mathbf{Q}^+\mathbf{r}$, where $\mathbf{r}_2$ is a vector of length M that is (nearly) independent of the data symbols $\mathbf{a}_d$. In the subset estimator, only $\mathbf{r}_2$ is considered, i.e. $\mathbf{r}_2 = \mathbf{B}_2\mathbf{h} + \mathbf{w}_2$, where $\mathbf{B}_2$ and $\mathbf{w}_2$ are respectively the parts of $\mathbf{Q}^+\mathbf{B}$ and $\mathbf{Q}^+\mathbf{w}$ corresponding to $\mathbf{r}_2$. The subset estimator is defined as

$$\hat{\mathbf{h}}_{subset} = (\mathbf{B}_2^+\mathbf{B}_2)^{-1}\mathbf{B}_2^+\mathbf{r}_2 \tag{9}$$

As for finite N, the equality $\mathbf{HF}_d = \tilde{\mathbf{F}}\tilde{\mathbf{H}}$ holds only approximately, the observation $\mathbf{r}_2$ is affected by a residual contribution from the data symbols $\mathbf{a}_d$, resulting in an error floor of the mean squared error (MSE) at high E_s/N_0 [1].

B. The Frequency Domain Estimator

In this section, we derive a new channel estimator following a similar reasoning as in [1]: we consider an invertible transform independent of the parameter to be estimated that results in a part of the observation to be data-free. However, in contrast with [1], we do not make any approximations. As it is impossible to find a linear transform independent of the channel vector $\mathbf{h}$ that makes the last ν samples of the observation interval data-free, a truly data-free observation consists of $M-\nu$ samples only.

Let us consider the following invertible transform:

$$\mathbf{r}' = \left(\begin{array}{c|c} \mathbf{F} & \mathbf{0} \\ \hline \mathbf{0} & \mathbf{I}_\nu \end{array}\right) \left(\begin{array}{c|c} \mathbf{I}_N & \begin{matrix}\mathbf{I}_\nu \\ \mathbf{0}\end{matrix} \\ \hline \mathbf{0} & \mathbf{I}_\nu \end{array}\right) \mathbf{r} \triangleq \mathbf{Tr} \tag{10}$$

where $\mathbf{I}_K$ is the $K\times K$ identity matrix. According to this transform, the last ν samples from the observation interval are added to the first ν samples (as indicated in figure 1b); this restores the orthogonality (over the first N samples) between the carriers of the OFDM system. Then an N-point FFT is applied to the first N samples (i.e. we convert these samples to the frequency domain) while the last ν samples are not transformed. As the carriers are orthogonal, data carriers do not interfere with pilot carriers. Hence, if we use as observation subset the $M-\nu$ FFT outputs at the pilot carrier positions only, these observations are data-free and ML estimation of the channel is simple.

The $M-\nu$ observations corresponding to the pilot carrier positions are given by

$$\mathbf{r}'_2 = \mathbf{B}'_2\mathbf{h} + \mathbf{w}'_2 \tag{11}$$

where the noise component $\mathbf{w}'_2$ is zero-mean Gaussian distributed with autocorrelation matrix $\mathbf{R}'_2$ given by

$$(\mathbf{R}'_2)_{k,k'} = N_0\left(\delta_{k,k'} + \frac{1}{N}\sum_{\ell=0}^{\nu-1} e^{-j2\pi\frac{(n_k-n_{k'})\ell}{N}}\right) \tag{12}$$

and $\mathbf{B}'_2 = \mathbf{B}'_p + \mathbf{B}'_g$ is a $(M-\nu)\times L$ matrix . The matrix $\mathbf{B}'_p$ corresponds to the contributions from the pilot carriers, i.e.

$$(\mathbf{B}'_p)_{k,\ell} = \sqrt{\frac{N}{N+\nu}}b_c(k)e^{-j2\pi\frac{k\ell}{N}} \qquad k\in I_p, \ell = 0,\dots,L-1 \tag{13}$$

and $\mathbf{B}'_g$ to the contributions from the guard interval pilots, i.e.

$$\mathbf{B}'_g = \sqrt{\frac{N}{N+\nu}}\mathbf{F}_{\nu,p}\mathbf{B}_{g,\nu} \tag{14}$$

where $(\mathbf{F}_{\nu,p})_{k,\ell} = \frac{1}{\sqrt{N}}e^{-j2\pi\frac{k\ell}{N}}$, $k\in I_p$, $\ell = 0,\dots,\nu-1$ and $(\mathbf{B}_{g,\nu})_{k,\ell} = b_g(|k-\ell|_\nu)$.

The ML estimate of $\mathbf{h}$ based on the observation $\mathbf{r}'_2$ is defined as [9]

$$\hat{\mathbf{h}}_{ML} = \arg\max_{\mathbf{h}} p(\mathbf{r}'_2|\mathbf{h}). \tag{15}$$

The ML estimate of $\mathbf{h}$ is easily found to be

$$\hat{\mathbf{h}}_{ML} = (\mathbf{B'}_2^+\mathbf{R'}_2^{-1}\mathbf{B'}_2)^{-1}\mathbf{B'}_2^+\mathbf{R'}_2^{-1}\mathbf{r}'_2 \tag{16}$$

and its MSE is given by

$$MSE = \text{trace}\left((\mathbf{B'}_2^+\mathbf{R'}_2^{-1}\mathbf{B'}_2)^{-1}\right). \tag{17}$$

To evaluate the behavior of the MSE (17), we approximate $\mathbf{B'}_2^+\mathbf{R'}_2^{-1}\mathbf{B'}_2$ by its average over all possible pilot sequences, i.e. $\mathbf{B'}_2^+\mathbf{R'}_2^{-1}\mathbf{B'}_2 = E[\mathbf{B'}_2^+\mathbf{R'}_2^{-1}\mathbf{B'}_2]$. We assume that the pilot symbols are selected in a pseudorandom way. Further, we neglect in (12) the second term. In that case, $E[\mathbf{B'}_2^+\mathbf{R'}_2^{-1}\mathbf{B'}_2]$ is essentially equal to

$$\begin{aligned}(E[\mathbf{B'}_2^+\mathbf{R'}_2^{-1}\mathbf{B'}_2])_{\ell,\ell'} &= \frac{N}{N+\nu}\frac{E_s}{N_0}\sum_{k\in I_p} e^{j2\pi\frac{k(\ell-\ell')}{N}} \\ &+ \frac{N}{N+\nu}\frac{1}{N_0}\frac{1}{N}\sum_{m,m'=0}^{L-1} e^{j2\pi\frac{k(m-m')}{N}}\,. \\ &\quad E[b_g^*(|m-\ell|_\nu)b_g(|m'-\ell'|_\nu)]\end{aligned} \tag{18}$$

When the pilot symbols are evenly distributed over the carriers and $M-\nu$ divides N, the first term in (18) reduces to $\frac{N}{N+\nu}\frac{E_s}{N_0}(M-\nu)\delta_{\ell,\ell'}$. The second term in (18) is of the order $L/N \ll M-\nu$, and therefore can be neglected as compared to the first term. Hence, $\mathbf{B'}_2^+\mathbf{R'}_2^{-1}\mathbf{B'}_2$ can be approximated by $\frac{N}{N+\nu}\frac{E_s}{N_0}(M-\nu)\mathbf{I}_L$, from which it follows that the MSE (17) can be approximated by

$$MSE = \frac{N+\nu}{N}\frac{N_0}{E_s}\frac{L}{M-\nu}, \tag{19}$$

i.e. the MSE is inversely proportional to the number of pilot carriers.

The matrices $\mathbf{B}'_2$ and $\mathbf{R}'_2$ depend only on the known pilot symbols and the known positions of the data carriers and the pilot carriers. Hence, $\mathbf{B}'_2$ and $\mathbf{R}'_2$ are known at the receiver and $(\mathbf{B'}_2^+\mathbf{R'}_2^{-1}\mathbf{B'}_2)^{-1}\mathbf{B'}_2^+\mathbf{R'}_2^{-1}$ can be precomputed. Therefore, the estimate (16) can be obtained with low complexity.

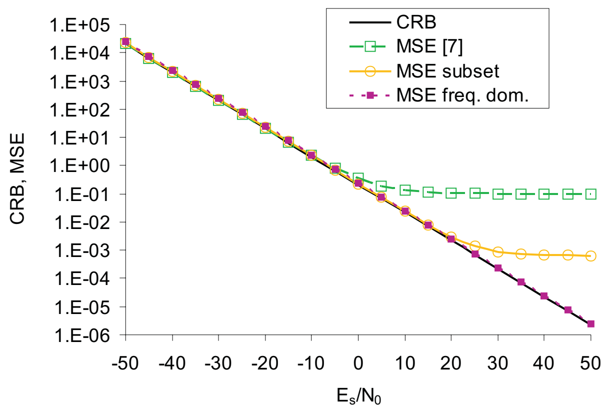

Fig. 2. MSE performance and CRB, $\nu = 7$, $N = 1024$, $M = 40$.

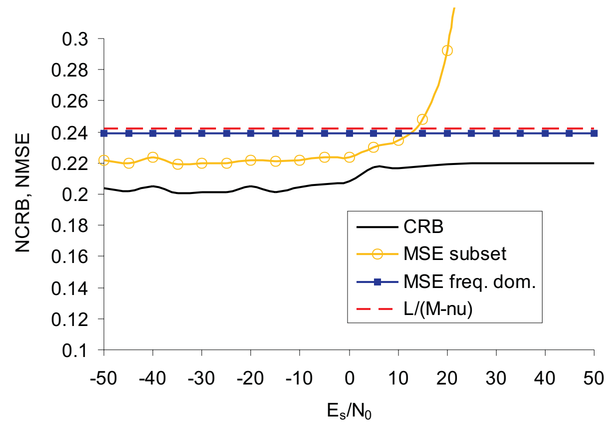

Fig. 3. Normalized MSE and CRB, $\nu = 7$, $N = 1024$, $M = 40$.

IV. Numerical Results

In this section, we evaluate the performance of the frequency domain estimator and compare it to the performance of the subset estimator. Without loss of generality, we assume the comb-type pilot arrangement [10] is used for the pilots transmitted on the carriers. Further, we assume $L = 8$ and $h(\ell) = h(0)(L-\ell)$, for $\ell = 0, \ldots, L-1$. The channel impulse response is normalized: $\sum_{\ell=0}^{L-1} |h(\ell)|^2 = 1$. The pilot symbols are randomly generated and BPSK modulated. We assume that the pilots are equally spaced over the carriers, i.e. the positions of the pilot carriers are $I_p = \{n_0 + m\delta | m = 0, \ldots, M-\nu-1\}$, where $\delta = \text{floor}(N/(M-\nu))$, $n_0 \in \{0, \ldots, \rho\}$ and $\rho = N-1-(M-\nu-1)\delta$.

In figure 2, the MSE of the frequency-domain estimator is shown as function of E_s/N_0. In addition, the MSE of the subset estimator and the MSE from the estimator from [7] are shown. As can be observed, the proposed frequency-domain estimator does not suffer from an error floor at high E_s/N_0, in contrast with the subset estimator and the estimator from [7]. Further, the CRB for data-aided channel estimation, derived in [1], is shown. It can be observed that the MSE of the proposed estimator is close to the CRB, and is inversely proportional to E_s/N_0.

To further evaluate the MSE's and the CRB from figure 2, we consider the normalized MSE (NMSE) and the normalized CRB (NCRB), defined as $NMSE = SNR \cdot MSE$ and $NCRB = SNR \cdot CRB$, where $SNR = \frac{N}{N+\nu}\frac{E_s}{N_0}$. From figure 3 it follows that at low E_s/N_0, the subset estimator slightly outperforms the frequency-domain estimator. The NMSE of the frequency domain estimator is constant with E_s/N_0, whereas the NMSE of the subset estimator strongly increases for high E_s/N_0. From the figure, it can be observed that the MSE resulting from the frequency-domain estimator is close to the CRB. Further, it follows from the figure that the NMSE of the frequency-domain estimator is close to $L/(M-\nu)$, as was shown in section III-B.

Figure 4 shows the influence of the number of pilots on the MSE of the frequency-domain estimator, assuming the pilots carriers are equally spaced. As expected (see (19)) the MSE

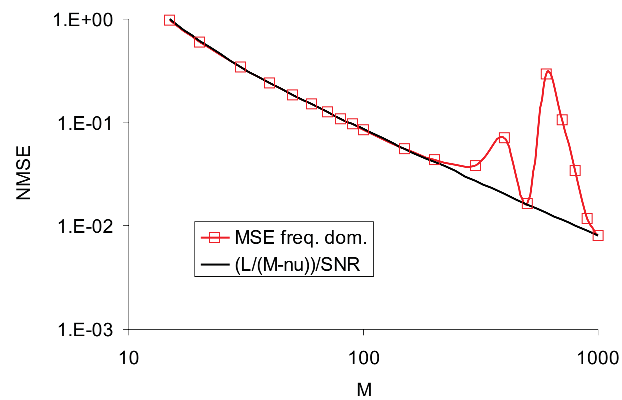

Fig. 4. Influence of M on the normalized MSE, $\nu = 7$, $N = 1024$.

is essentially equal to $\frac{L}{M-\nu} SNR^{-1}$ for a wide range of M, i.e. the MSE is inversely proportional to the number of pilot carriers. For large M, the pilot spacing becomes $\epsilon = 2$ (for $N/4 < M-\nu < N/2 = 512$) and $\epsilon = 1$ (for $M-\nu > N/2 = 512$); in that case pilots are not evenly spread over the carriers but grouped in one part of the spectrum, such that the first term in (18) can no longer be approximated by $SNR(M-\nu)\delta_{\ell,\ell'}$. This causes the peaks in the figure.

The influence of random pilot carrier positions on the frequency domain estimator performance is shown in figure 5. In this figure, the MSE is shown for 50 randomly generated pilot carrier positions, along with the average over the simulations. Further, the MSE is shown for equally spaced pilot positions. For small M, we observe that the performance of the frequency domain estimator strongly depends on the pilot positions, whereas for large M, the frequency domain estimator becomes essentially independent of the pilot positions. Hence, for small M, fixed, equally spaced pilot positions are preferred. For large M, equally spaced pilot positions are not suitable because of the peak in the MSE. Therefore, at large M, random pilot positions are advised.

In figure 6, the effect of the FFT length N on the performance of the frequency domain estimator and the subset

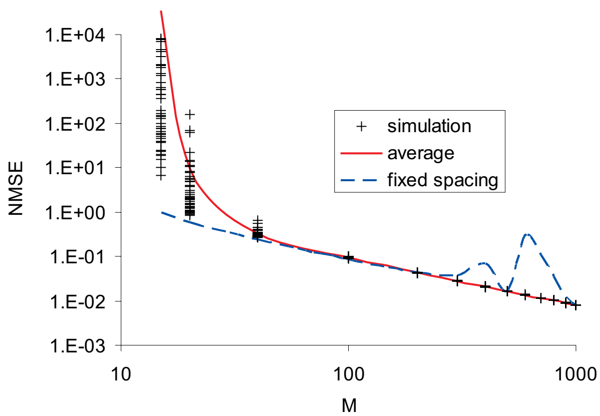

Fig. 5. Influence of the pilot positions on the normalized MSE, $\nu = 7$, $N = 1024$.

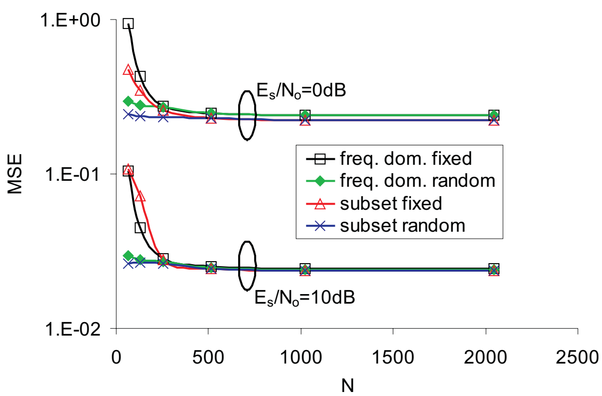

Fig. 6. Influence of the FFT length N on the MSE, $M = 40$, $\nu = 7$.

estimator is shown, for both fixed and random pilot positions. In the figure, the MSE corresponding to the best random pilot positioning, i.e. with the lowest MSE, out of 50 randomly generated pilot positionings is shown. At low N, equally spaced pilot positions perform worse than randomly spaced pilot positions, for both estimators. For larger N, both kinds of pilot symbol positions yield essentially the same MSE, especially for moderate to large SNR. Further, it can be observed that the MSE is essentially independent of the FFT length, especially for the random pilot positions.

V. Conclusions

In this paper, we have proposed a low-complexity data-aided channel estimator for KSP-OFDM, that operates in the frequency domain. This estimator exploits only the $M - \nu$ FFT outputs at the pilot carrier positions. In contrast with the subset estimator from [1], the proposed estimator does not suffer from an error floor in the MSE performance at high SNR, because the pilot carriers are not affected by the data carriers. At low SNR, the proposed estimator performs only slightly worse than the subset estimator.

The MSE of the proposed estimator is inversely proportional to the SNR. Further, the MSE is inversely proportional to the number of pilot carriers; it is essentially proportional to $L/(M - \nu)$. At low M, the MSE strongly depends on the pilot carrier positions, whereas at high M, the performance is essentially independent of the pilot positions. Further, the MSE is essentially independent of the FFT size.

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