Channel Estimation in OFDM Systems with Strong Interference

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***Abstract*— In this paper, we investigate channel estimation algorithms in an OFDM system which is exposed to pulsed interference. It will be examined how the interference affects the performance of the channel estimation and how the channel estimation can be adapted to cope with the interference. The performance of the channel estimation will be given by means of the mean square error. In addition, bit error rate curves of the overall OFDM system will be presented to confirm the beneficial influence of the adaption.**

I. Introduction

The estimation of the transmission channel is an important part of each coherent OFDM transmission, where the equalization of the received data is based on accurate estimates of the channel transfer function. One distinguishes between a blind estimation of the channel transfer function and pilot symbol based channel estimation (CE) algorithms, where known pilot symbols are inserted at certain subcarriers in certain OFDM symbols. Based on the receiver pilot symbols, the channel coefficients at pilot positions can be obtained easily and the unknown channel coefficients at data positions are interpolated. In this paper, we will focus on pilot based CE algorithms, namely a linear interpolation of the channel coefficients between two adjacent pilot symbols and a Wiener interpolation. The coefficients of the Wiener interpolation filter are derived by minimizing the mean-square-error (MSE) between the actual and the estimated channel coefficients. This leads to an optimal noise suppression, given the noise variance and channel statistics. These two approaches are widely studied [1], [2] and their performance is well known for mobile communication channels. However, the channel estimation suffers from interference, as it may occur in the aeronautical environment. Especially distance measuring equipment (DME) imposes strong interference pulses [3]. This is a critical issue especially in pilot-based approaches, as corrupted pilot symbols will lead to deficient estimates at the adjacent data positions which are not necessarily affected by interference. This requires an adaption of the CE algorithms to the interference. In this paper, we propose to estimate and incorporate the interference power into the CE. We investigate how the interference power can be interpreted as a measure for the quality of the pilot symbols and how the pilot symbols can be weighted when interpolating the channel coefficients at data positions.

The paper is organized as follows: in the next section, we introduce the interference scenario and present algorithms for estimating the interference power. In Section III, the CE algorithms will be described, mainly focusing on the adaption to the interference. Afterwards, we will present simulations results, showing the performance of the CE in terms of the MSE and of the overall system in terms of the bit-error-rate (BER). Finally, Section V summarizes the paper.

II. Characterization and Estimation of Interference

A. Characterization of Interference

As interference model, a DME signal is chosen, which consists of pairs of Gaussian-shaped pulses. One pulse pair in the base band writes

$$i_{\mathrm{DME}}(t) = e^{-\alpha t^2/2} + e^{-\alpha (t-\Delta t)^2/2}, \tag{1}$$

with $\Delta t = 12\,\mu\mathrm{s}$ or $\Delta t = 36\,\mu\mathrm{s}$ defining the interval between the two pulses. The parameter $\alpha = 3.5\,\mu\mathrm{s}$ specifies the pulse duration. For the DME signal in the frequency domain, one obtains after short calculation

$$I_{\mathrm{DME}}(f) = \sqrt{\frac{8\pi}{\alpha}} e^{\left(2\pi^2 f^2/\alpha\right)} e^{(-j\pi f \Delta t)} \cos\left(\pi f \Delta t\right). \tag{2}$$

The shape of the DME interference is still Gaussian in the frequency domain, however the pair of pulses leads to a modulation with a cosine function.

These DME pulses are modulated on integer multiples of $1\,\mathrm{MHz}$ in the aeronautical L-band (960-1215 MHz), leading to a frequency spacing between

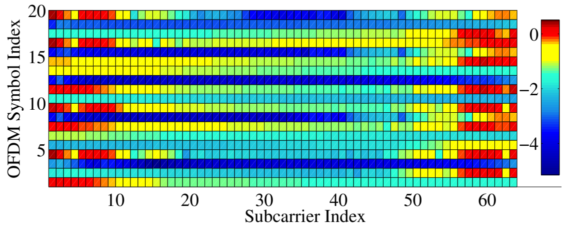

Fig. 1. DME interference power affecting the OFDM transmission bandwidth.

two adjacent DME channels of $1\,\mathrm{MHz}$. When operating an OFDM transmission with a bandwidth of $B_{\mathrm{OFDM}} = 625\,\mathrm{kHZ}$ as defined in [4] between two consecutive DME channels, one obtains a typical interference situation for the OFDM transmission as depicted in Fig. 1. The occurence of DME pulse pairs is given in pulse pairs per second (ppps). DME ground stations transmit with up to $3600\,\mathrm{ppps}$.

The inlay approach of the OFDM transmission between two adjacent DME channels and the Gaussian shape of the interference leads to a slopy interference power profile, with high interference power at the edges of the transmission bandwidth and low in the middle of the OFDM bandwidth. Another issue of pulsed interference in combination with OFDM, which is pointed out by Fig. 1, is the fact that the interference is uncorrelated in time direction, as the fast Fourier transform (FFT) is applied separately to each OFDM symbol.

B. *Interference Estimation*

The estimation of the interference power exploits the known spectral shape of DME interference, given by (2). An OFDM transmission usually exhibits empty subcarriers at the edge of the spectrum, referred to as guard bands. In the guard band, the interference power level can be measured and the spectrum of the interference signal $\tilde{I}_{\mathrm{DME}}(f)$ on all subcarriers can be reconstructed [5]. Thereby, the spectral shape of the DME signal is assumed either to decay linearly, as depicted in Fig. 2, or the actual DME spectrum is approximated based on known spectral characteristics of Gaussian shaped pulses.

Since the linear approximation performs only marginally worse compared to the Gaussian approximation (see [5]) and the Gaussian approximation is more prone to estimation errors and frequency misalignments, we will apply the linear approximation. In Fig. 2 one remarks that the interference power in the middle of the spectrum is slightly overestimated. This is tolerable as the interference power in the middle of the spectrum is very low and it is more important to estimate the high interference power at

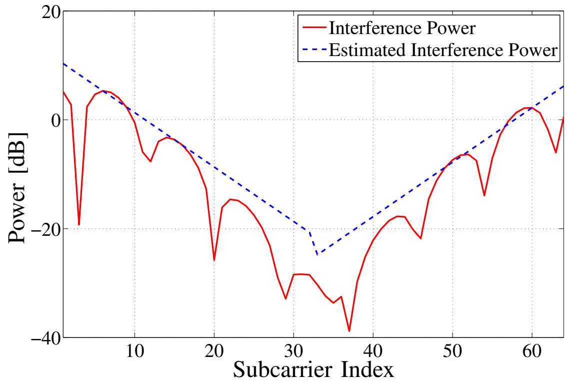

Fig. 2. Illustration of Interference Estimation.

the edges of the spectrum correctly. The power of the estimated interference signal writes

$$P^{I}(f) = |\tilde{I}_{\mathrm{DME}}(f)|^2. \tag{3}$$

III. Channel Estimation

In this paper, we will focus on pilot-based channel estimation algorithms. After the FFT in the receiver (Rx), the signal is composed of the transmitted OFDM signal X, the channel coefficients H, a noise term N, and the interference I and is described by

$$Y_{n,l} = H_{n,l}X_{n,l} + N_{n,l} + I_{n,l}. \tag{4}$$

Here, n denotes the subcarrier index and l the OFDM symbol number. At pilot positions $\{n', l'\} \in \mathcal{P}_1$, one obtains the estimated channel coefficients by dividing the Rx signal by the known transmitted pilot symbols

$$\tilde{H}_{n',l'} = \frac{Y_{n',l'}}{X_{n',l'}} = H_{n',l'} + \frac{N_{n',l'} + I_{n',l'}}{X_{n',l'}}. \tag{5}$$

To improve CE, pilot boosting is applied. In this case, the power of the pilot symbols is increased by $4\,\mathrm{dB}$ over the average power of each data symbol. For further calculations, we define for pilots symbols

$$\gamma = E\left\{|X_{n',l'}|^2\right\}. \tag{6}$$

For further investigations an OFDM frame as depicted in Fig. 3, taken from [4] was adopted. The non-rectangular pattern was chosen to make CE robust towards interference by diminishing the number of pilot symbols, which are affected in case an OFDM symbol coincides with a strong interference pulse. The pilot distances have been chosen to comply with the coherence time and coherence bandwidth, which were derived from the expected Doppler and delay distributions of the aeronautical en-route channel. In the following, linear and Wiener interpolation will be presented.

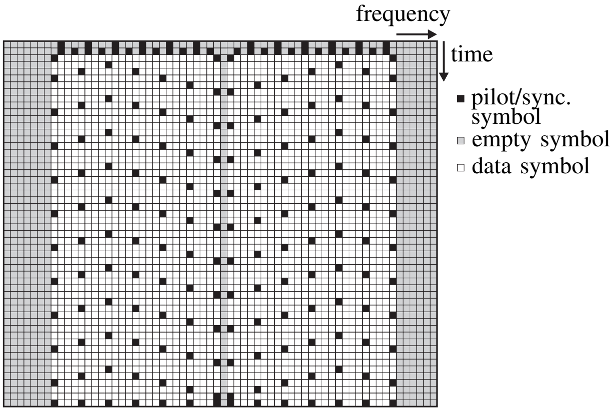

Fig. 3. OFDM frame with pilot symbols.

A. Linear interpolation

The linear interpolation is subdivided in a one-dimensional interpolation in time direction and a subsequent interpolation in frequency direction. The linear interpolation in time direction is described by

$$\tilde{H}'_{n',l'+i} = \frac{N_{\mathrm{t}} - i}{N_{\mathrm{t}}} \tilde{H}_{n',l'} + \frac{i}{N_{\mathrm{t}}} \tilde{H}_{n',l'+N_{\mathrm{t}}}, \quad i = 1, \ldots, N_{\mathrm{t}} - 1. \tag{7}$$

The subsequent interpolation in frequency direction is based on $\tilde{H}_{n'',l''}$ and $\tilde{H}'_{n'',l''}$, $\{n'', l''\} \in \mathcal{P}_2$ with $\mathcal{P}_2$ being the set of pilot positions and positions of interpolated channel coefficients in the first step. Mathematically, it is described similar to (7) by

$$\hat{H}_{n''+j,l''} = \frac{N_{\mathrm{f}} - j}{N_{\mathrm{f}}} \tilde{H}'_{n'',l''} + \frac{j}{N_{\mathrm{f}}} \tilde{H}'_{n''+N_{\mathrm{f}},l''}, \quad j = 1, \ldots, N_{\mathrm{f}} - 1. \tag{8}$$

B. Wiener interpolation

Like the linear interpolation, the Wiener interpolation is split up in two one-dimensional interpolations. The derivation of the Wiener filter is well known, e.g. [2], and one obtains for the interpolation in time direction

$$\tilde{H}'_{n',l} = \sum_{m=1}^{P_t} w_m^{n',l} \tilde{H}_{n',l'_m}, \tag{9}$$

with P_t being the number of pilot symbols within an OFDM frame at a certain subcarrier. The filter coefficients $w_m^{n',l}$ are given by

$$\mathbf{w}_{n',l}^T = \mathbf{r}_{H\tilde{H},n',l}^T \cdot \mathbf{R}_{\tilde{H}\tilde{H},n'}^{-1}. \tag{10}$$

The vector $\mathbf{w}_{n',l}^T$ comprises all P_t filter coefficients for the data subcarrier $\{n', l\}$. $\mathbf{r}_{H\tilde{H},n',l}^T$ contains the cross-covariance values between this data subcarrier and the pilot symbols at the n'th subcarrier and $\mathbf{R}_{\tilde{H}\tilde{H},n'}$ is composed of the auto-covariance values between these pilot symbols. For a detailed description, see [6]. The MMSE of this interpolation is described by

$$E\left\{|\tilde{H}'_{n',l} - H_{n',l}|^2\right\} = J_{\min}^{n',l} = 1 - \mathbf{r}_{H\tilde{H},n',l}^T \cdot \mathbf{R}_{\tilde{H}\tilde{H},n'}^{-1} \cdot \mathbf{r}_{H\tilde{H},n',l}^*. \tag{11}$$

For the subsequent interpolation in frequency direction, a filter similar to (9) has to be defined

$$\hat{H}_{n,l''} = \sum_{m=1}^{P_f} v_m^{n,l''} \tilde{H}'_{n''_m,l''}, \tag{12}$$

with the number of subcarriers containing pilot symbols P_f. According to (10), the filter coefficients can be calculated by

$$\mathbf{v}_{n,l''}^T = \mathbf{r}_{H\tilde{H},n,l''}^T \cdot \mathbf{R}_{\tilde{H}\tilde{H},l''}^{-1}. \tag{13}$$

Since this interpolation is based not only on pilot symbols, but also on estimates from (9), one has to incorporate $J_{\min}$ when calculating $\mathbf{r}_{H\tilde{H},n,l''}^T$ and $\mathbf{R}_{\tilde{H}\tilde{H},l''}$, as it is described in [6]. Note that the results from [6] has to be extended to a non-rectangular pilot grid. The cross- and auto-covariance functions in time- and frequency direction are derived from the Doppler and delay power spectrum. We assumed a uniform distribution for these spectra, based on the maximum delay and Doppler of the investigated channel model.

C. Interference adaption

For adapting the CE, the quality of the channel coefficients at pilot positions has be taken into account. This quality can be judged by the interference power. One approach, named pilot erasure setting, is to set a channel coefficient at a pilot position to zero, if the estimated interference power $P_{n',l'}^I$ exceeds a certain threshold, e.g. the power of the useful OFDM signal, as already proposed in [7]. The idea behind pilot erasure setting is the assumption that no information about the channel is better than wrong information, coming along with a interference power higher than the useful OFDM signal power. Mathematically this can be described by a multiplication with a factor $\alpha_{n',l'}$, which is defined by

$$\alpha_{n',l'} = \begin{cases} 1, & P_{n',l'}^I < \gamma \\ 0, & P_{n',l'}^I \geq \gamma \end{cases}.$$

Another approach is to weight the channel coefficients according to the estimated interference power normalized by the interference-free noise power $2\sigma^2$. In this case the attenuation factor $\alpha_{n',l'}$ is defined by

$$\alpha_{n',l'} = \frac{2\sigma^2}{2\sigma^2 + P_{n',l'}^I}. \tag{14}$$

Both approaches does not depend on the CE algorithm, i.e. can be applied to linear interpolation as well as to Wiener interpolation. One should keep in mind that erasing or weighting channel coefficients will lead to attenuated, thus wrong amplitudes of the interpolated channel coefficients, but the phase estimation is expected to be improved by the weighting. When using QPSK as modulation scheme, this turns out to be advantageous, as QPSK is a phase modulation technique and the amplitudes can be seen as an inherent reliability information.

Another approach which avoids this amplitude attenuation and can be applied to Wiener interpolation is to incorporate the interference power into the noise power. The structure of the auto-covariance matrix $\mathbf{R}_{\tilde{H}\tilde{H},n'}$ from (10) is given by

$$\mathbf{R}_{\tilde{H}\tilde{H},n'} = \begin{pmatrix} R_{t;n',(l'_1-l'_1)}+\beta & \cdots & R_{t;n',(l'_1-l'_{P_t})} \\ \vdots & \ddots & \vdots \\ R_{t;n',(l'_{P_t}-l'_1)} & \cdots & R_{t;n',(l'_{P_t}-l'_{P_t})}+\beta \end{pmatrix}, \quad (15)$$

with $\beta = 2\sigma^2/\gamma$ and $R_{t;n',(l'_x-l'_y)}$ being the covariance in time direction between the pilot positions $\{n', l'_x\}$ and $\{n', l'_y\}$. The interference power can simply be included by interpreting the interference as additional impulsive noise and modifying β as follows

$$\beta_{n',l'} = \frac{2\sigma^2 + P^I_{n',l'}}{\gamma}. \quad (16)$$

Note that $\beta_{n',l'}$ is now different for each entry on the main diagonal of the auto-covariance matrix.

IV. Simulation Results

The performance of CE and the suitability of the CE adaption is evaluated in a realistic interference scenario. The interference scenario is retrieved from real DME channel assignments in the area around Paris, France, as this is the area with the highest density of DME stations in Europe. The parameters of this scenario are given in Tab. I.

TABLE I
EN-ROUTE INTERFERENCE SCENARIO

Station	Frequency	Interference power at victim Rx input	Pulse rate
DME	995 MHz	−67.9 dBm	3600 ppps
OFDM	995.5 MHz		
DME	996 MHz	−74.0 dBm	3600 ppps
DME	996 MHz	−90.3 dBm	3600 ppps

The basic parameters of the OFDM system that is operated in the spectral gap between two adjacent DME channels are listed in Tab. II. For coding and modulation, a $(133, 171)$ convolutional code with rate $1/2$ in concatenation with a Reed-Solomon code of rate 0.9 and QPSK modulation are applied. Propagation through the radio channel is modeled by an appropriate en-route channel model taking into account a strong line-of-sight path, Doppler frequencies of up to 1.05 kHz, and two delayed paths. Note, although the maximum path delay does not exceed 15 µs the length of the cyclic prefix is much longer. The additional samples are employed in the OFDM transmitter for transmit windowing in order to reduce out-of-band radiation.

TABLE II
OFDM SYSTEM PARAMETERS

Parameter	Value
Used bandwidth	498.0469 kHz
Subcarrier spacing	9.7656 kHz
FFT length N	64
Sampling rate	625 kHz
OFDM symbol duration	96 µs
Cyclic prefix	24 µs
Total OFDM symbol duration	120 µs

The performance of CE is given in terms of the MSE in Fig. 4. The Figure shows that the Wiener interpolation outperforms the linear interpolation in the interference-free as well as in the interference case. The gain is about 6 dB at MSE $= 4{\cdot}10^{-2}$. Interference impairs the CE significantly and the performance of the CE degrades for Wiener interpolation more than 7 dB. However, when incorporating the interference power into the noise power when applying Wiener interpolation, the performance improves greatly and the interference-free case is reached by 1.5 dB.

As pilot erasure setting and pilot weighting imply an attenuation of the interpolated channel coefficients, it is hardly possible to assess the quality of the phase estimation, which is crucial for QPSK,

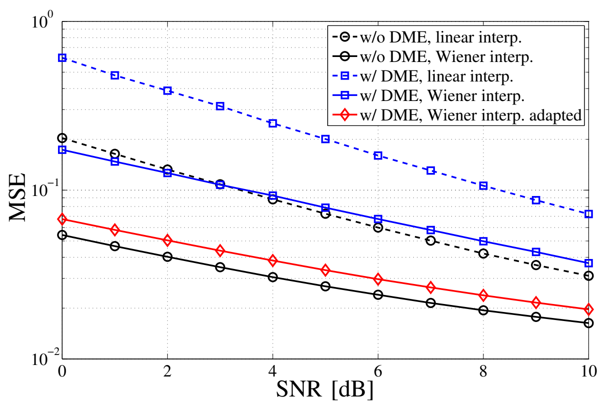

Fig. 4. MSE of the channel estimation for linear and Wiener interpolation.

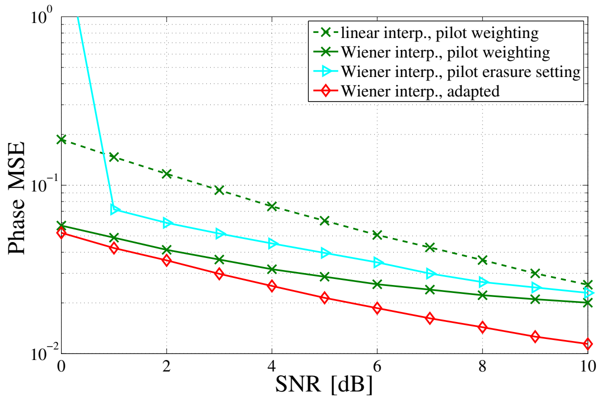

Fig. 5. Phase MSE of the channel estimation for different interference adaption methods.

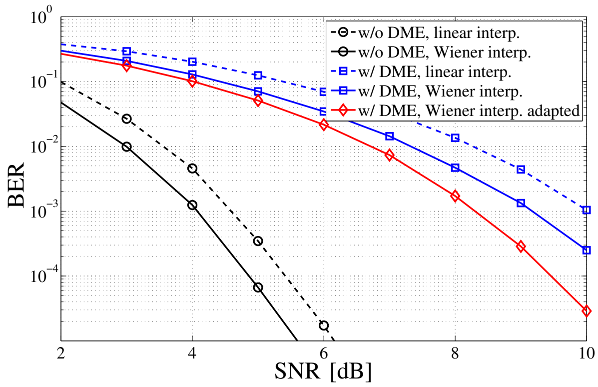

Fig. 6. BER of OFDM system with Wiener interpolation.

by the common MSE. Thus the MSE of the phase of the estimated channel coefficients are a more suitable measure for the quality of the channel estimation in this case. This phase MSE is given in Fig. 5 for the different interference adaption methods. For Wiener interpolation, the simple pilot erasure setting leads to the worst results, which is not astonishing as the interference power is mapped only very coarse onto the CE. A better result is achieved when weighting the pilot symbols with the interference power, this leads to a gain of $2.5\,\mathrm{dB}$ at MSE $= 3 \cdot 10^{-2}$. An additional gain of $1.5\,\mathrm{dB}$ can be realized when incorporating the interference into the noise power, leading also to correct unaltered amplitude estimates, which is beneficial for higher order modulation alphabets or iterative Rx structures. For linear interpolation, e.g. with pilot weighting, the performance is considerably worse compared to Wiener interpolation ($4.5\,\mathrm{dB}$ at MSE $= 3 \cdot 10^{-2}$).

Finally the BER of the overall OFDM system when applying Wiener interpolation is depicted in Fig. 6. It becomes obvious that the interference affects the useful OFDM signal heavily and leads to a degradation of $5.1\,\mathrm{dB}$ in terms of the SNR at BER $= 1 \cdot 10^{-3}$. This gap can be reduced by $0.9\,\mathrm{dB}$ when applying the interference into noise incorporation of the Wiener interpolation. This does not seem to be a lot, however when keeping the MSE performance of this adaption in mind (see Fig. 4) it looks as if the remaining loss arises mainly from the data impairment by the interference and any further improvement should be achieved by interference mitigation techniques, but not by a more sophisticated CE.

V. Summary

In this paper, channel estimation for OFDM systems, especially in the case of strong interference is investigated. It pointed out that Wiener interpolation outperforms a linear interpolation in the interference-free and in the interference case. However both channel estimation techniques suffer from the interference, leading to deficient result. We showed that applying simple adaption techniques as pilot erasure setting and pilot weighting improves the performance significantly. When incorporating the interference power directly into the noise power for Wiener interpolation, the performance improves even more and the interference-free case is reached by $1.5\,\mathrm{dB}$ at MSE $= 4 \cdot 10^{-2}$. For future work, one could think about incorporating the estimated interference power not only in the CE but also e.g. in the demodulation block.

References

[1] S. Coleri, M. Ergen, A. Puri, and Ahmad Bahai, "Channel estimation techniques based on pilot arrangement in OFDM systems," *IEEE Transactions on Broadcasting*, vol. 48, no. 3, pp. 223–229, September 2002.

[2] P. Hoeher, S. Kaiser, and P. Robertson, "Two-dimensional pilot-symbol-aided channel estimation by wiener filtering," in *Proc. IEEE ICA SSP*, Munich, Germany, April 1997, pp. 1845–1848.

[3] Grace Xingxin Gao, "DME/TACAN Interference and its Mitigation in L5/E5 Bands," in *ION Institute of Navigation Global Navigation Satellite Systems Conference*, Fort Worth, TX, USA, September 2007.

[4] M. Sajatovic, B. Haindl, M. Ehammer, Th. Gräupl, M. Schnell, U. Epple, and S. Brandes, "L-DACS1 System Definition Proposal: Deliverable D2," Tech. Rep., Eurocontrol, Issue 1.0, February 2009.

[5] M. Schnell, S. Brandes, S. Gligorevic, M. Walter, C. Rihacek, M. Sajatovic, and B. Haindl, "Interference Mitigation for Broadband L-DACS," in *27th Digital Avionics Systems Conference (DASC)*, St. Paul, MN, USA, October 2008, pp. 2.B.2–1 – 2.B.2–12.

[6] S. Jelting F. Sanzi and J. Speidel, "A comparative study of iterative channel estimators for mobile OFDM systems," *IEEE Transactions on Wireless Communications*, pp. 849–859, September 2003.

[7] S. Brandes, U. Epple, S. Gligorevic, M. Schnell, B. Haindl, and M. Sajatovic, "Physical Layer Specification of the L-band Digital Aeronautical Communications System (L-DACS1)," in *2009 Integrated Communications, Navigation, and Surveillance (ICNS) Conference*, Arlington, VA, USA, May 2009.