COMPARISON OF PILOT MULTIPLEXING SCHEMES FOR ML CHANNEL ESTIMATION IN CODED OFDM-CDMA

Martin Feuersänger, Florian Hasenknopf, Volker Kühn and Karl-Dirk Kammeyer

Abstract As bandwidth is becoming precious, spectral efficiency is nowadays one of the key parameters of mobile radio communications. To reach high spectral efficiency in Code Division Multiple Access systems, combating multi-user interference is inevitable. Especially in an uplink scenario this can be done by applying multi-user detection. This paper compares two multiplexing schemes for pilot data in a system with combined maximum likelihood channel estimation (MLCE) and successive interference cancellation (SIC).

It is shown that even though preceding pilots deliver a better initial channel estimate a scheme with IQ-mapped pilots leads to better performance when using a combined MLCE-SIC receiver.

1. Introduciton

Today Code Division Multiple Access (CDMA) is widely used as an efficient scheme to acquire multiple access to mobile radio channels. In combination with OFDM (Orthogonal Frequency Division Multiplex) a Multi-Carrier-CDMA realization can be achieved where chips are only affected by flat fading [1, 2] thus leading to efficient transmitter and receiver structures.

Interference caused by access of multiple users (MUI) is therefore the prime reason for a limited system capacity in an uplink scenario. Multi-user detection (MUD) [3, 4], especially when integrated in iterative structures [5, 6, 7, 8, 9], largely improves spectral efficiency of MUI-degraded systems.

In this paper coarse synchronization is assumed thus leading to a quasi-synchronous system where remaining asynchronism is compensated by the inherent cyclic prefix. Nonlinear successive interference cancellation (SIC) is applied to combat multi-user interference. A maximum likelihood channel estimation (MLCE) and SIC are combined as described in [10] yielding iteratively improved channel and data estimates. Transmission is organized in frames where each frame again is split in a number of fading blocks where the number depends on the

channel characteristics.
We compare two approaches of training data structures for channel estimation. In a first setup we apply pilot symbols preceding data symbols of each fading block thus generating a time multiplexed system of pilots and data (TM-system). In a second setup, the pilot data is mapped onto the imaginary part of the QPSK symbols which is based on training structure setup of UMTS [11] - we will refer to it as IQ-multiplexed system (IQ-system)
The paper is organized as follows: Section 2 describes the OFDM-CDMA system. Next, section 3 explains the combination of channel estimation with SIC and their adaptation to the two different training data realizations. In section 4 we present simulation results of these two realizations and analyze their performance. Section 5 summarizes the results of this paper.

2. OFDM-CDMA System

Figure 1 depicts the considered OFDM-CDMA transmitter. Each user u is transmitting L_d information bits $\mathbf{d}_u$ that are encoded by identical convolutional codes of rate $R_c = 1/2$ and constraint length $L_c = 3$. These coded bits $\mathbf{b}_u$ are interleaved by user-specific interleavers $\Pi_t^{(u)}$ with a length of $L_b = 2L_d$.
While $\mathbf{b}_u$ is mapped onto QPSK symbols in the TM case, the first $L_{p,\mathrm{IQ}}$ QPSK symbols of the IQ-system consist of $L_{p,\mathrm{IQ}}$ bits out of $\mathbf{b}_u$ determining the real part and $L_{p,\mathrm{IQ}}$ pilot bits out of $\mathbf{p}_u$ for the imaginary part. The remaining $L_b - L_p$ bits in $\mathbf{b}_u$ are mapped to QPSK symbols . This leads to $L_{p,\mathrm{IQ}} = 2L_{p,\mathrm{TM}}$ OFDM symbols in the IQ-system carrying pilot data.
The complex QPSK symbols are spread separately in real and imaginary part by a factor of $N_s = 32$ using pseudo random long codes $\mathbf{c}_u$. The load of the system is defined as $\beta = U/N_s$ where U is the number of users in the system ($1 \leq u \leq U$).
The spread sequence $\mathbf{x}_u$ is then transformed into the time domain. The number

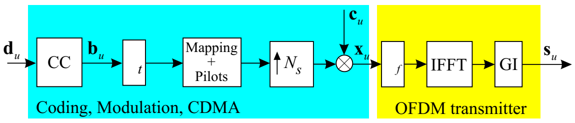

Figure 1. Block diagram of OFDM-CDMA transmitter

of carriers N_c is equal to $N_c = nN_s = 64$. After interleaving over N_c chips in frequency direction an inverse Fourier transform is applied. Each OFDM symbol is preheaded by a cyclic prefix with the duration T_g. The resulting signal $\mathbf{s}_u$ is then transmitted over the channel. After inversing the transform at the receiver this implies that each chip is only affected by multiplicative flat fading.

2.1 Channel Model

As we are investigating an uplink scenario all users are transmitted over U individual 4-path Rayleigh block fading channels. The impulse response of the channel remains constant over a fading block consisting of L_f OFDM symbols. Impulse responses of successive fading blocks are statistically independent. At the receiver, the cyclic prefix is removed. One FFT window is adequate for transforming all users back into the frequency domain when assuming that the guard interval compensates residual delays which are left over after coarse synchronization. This leads to the received vector $\mathbf{r}$.

2.2 Simulation Parameters and Pilot Setup

We assume a signal bandwidth of $B = 5$ MHz, i.e. OFDM symbols are $T_s = 6.4\,\mu$s in duration. The chosen block length is $L_f = 20$ OFDM symbols. The proportions of pilots to data are based on slot format #3 of the uplink FDD mode defined in [11], i.e. a frame incorporates 35% training data. Hence, the number of QPSK training symbols for the TM-system equals $L_{p,\mathrm{TM}} = 7$. In the IQ-system 70% of the QPSK symbols carry training information in the imaginary part. The maximum number of iterations N_{it} for the SIC is 16.

3. Combined Channel Estimation and Multi-user Detection

Figure 2 shows a schematic of the combination of channel estimation and successive interference cancellation. After initial ML channel estimation over all U channel impulse responses the first SIC iteration is executed. After FEC decoding of all user signals the reconstructed data is fed back to the channel estimation where it is used as additional pseudo-training data for an improved channel estimation that can now exploit the whole length of the fading block. Based on these estimates the next iteration of the SIC is executed. This process is repeated until no further improvement is achieved or the maximum number of iterations N_{it} is reached.

3.1 Initial Channel Estimation

The initial estimate of the U user-specific channels differs for the TM- and the IQ-system. Training data is obtained from different positions in the QPSK symbol-stream. The training data of the IQ-system is additionaly disturbed by the data component in the real part of the QPSK symbols.

Let $\mathbf{P}$ be a $L_{p,\mathrm{TM}} \times U$ resp. $L_{p,\mathrm{IQ}} \times U$ matrix containing as diagonal submatrices those OFDM symbols carrying training information. $\mathbf{T}_{\mathrm{DFT}}\mathbf{h}$ represents the channel transfer function in its time representation taking into account a L-tap

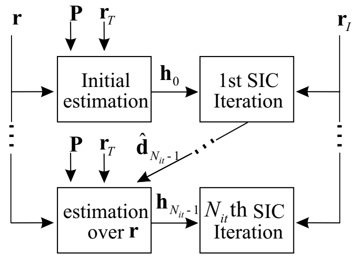

Figure 2. Combined ML Channel Estimation and Successive Interference Cancellation

impulse response. For the TM-system we receive during the training period

$$\mathbf{r}_{T,\mathrm{TM}} = \mathbf{P}\mathbf{T}_{\mathrm{DFT}}\mathbf{h} + \mathbf{n}_T \tag{1}$$

If we define $\tilde{\mathbf{P}} := \mathbf{P}\mathbf{T}_{\mathrm{DFT}}$, the maximum likelihood (ML) estimate of the channel impulse response for the TM-system is

$$\hat{\mathbf{h}}_{\mathrm{MLCE,TM}} = (\tilde{\mathbf{P}}^H\tilde{\mathbf{P}})^{-1}\tilde{\mathbf{P}}^H\mathbf{r}_T = \mathbf{h} + (\tilde{\mathbf{P}}^H\tilde{\mathbf{P}})^{-1}\tilde{\mathbf{P}}^H\mathbf{n}_T \tag{2}$$

showing that the estimate of h is disturbed by a modified AWGN term $\tilde{\mathbf{n}}_{T,\mathrm{TM}} = (\tilde{\mathbf{P}}^H\tilde{\mathbf{P}})^{-1}\tilde{\mathbf{P}}^H\mathbf{n}_T$. For the IQ-system we receive during the training period

$$\mathbf{r}_{T,\mathrm{IQ}} = (\mathbf{X} + j\mathbf{P})\mathbf{T}_{\mathrm{DFT}}\mathbf{h} + \mathbf{n}_T, \tag{3}$$

where $\mathbf{X}$ represents the unknown data in the real part of the QPSK symbols. The ML channel estimate for the IQ-system can now be derived as

$$\hat{\mathbf{h}}_{\mathrm{MLCE,IQ}} = -j(\tilde{\mathbf{P}}^H\tilde{\mathbf{P}})^{-1}\tilde{\mathbf{P}}^H\mathbf{r}_T. \tag{4}$$

The IQ-system contains additional interference caused by unknown data in the real part of the QPSK symbols containing also the training data. The initial estimate of the IQ-system is of the form

$$\hat{\mathbf{h}}_{\mathrm{MLCE,IQ}} = \mathbf{h} - j(\tilde{\mathbf{P}}^H\tilde{\mathbf{P}})^{-1}\tilde{\mathbf{P}}^H\tilde{\mathbf{X}} - j(\tilde{\mathbf{P}}^H\tilde{\mathbf{P}})^{-1}\tilde{\mathbf{P}}^H\mathbf{n}_T. \tag{5}$$

Just like $\tilde{\mathbf{P}}$ we have defined $\tilde{\mathbf{X}} := \mathbf{X}\mathbf{T}_{\mathrm{DFT}}$. Besides the modified AWGN contribution $\tilde{\mathbf{n}}_{T,\mathrm{IQ}} = -j(\tilde{\mathbf{P}}^H\tilde{\mathbf{P}})^{-1}\tilde{\mathbf{P}}^H\mathbf{n}_T$ we get an aditional interference term $\tilde{\mathbf{n}}_{X,\mathrm{IQ}} = -j(\tilde{\mathbf{P}}^H\tilde{\mathbf{P}})^{-1}\tilde{\mathbf{P}}^H\tilde{\mathbf{X}}$. Since $\tilde{\mathbf{P}}$ for the IQ-system is twice as long for the TM-system but each element contains only half power since only the imaginary part is considered we can state that $\tilde{\mathbf{n}}_{T,\mathrm{IQ}}$ and $\tilde{\mathbf{n}}_{T,\mathrm{TM}}$ have equal power. This leaves the IQ-system with the additional interference term $\tilde{\mathbf{n}}_{X,\mathrm{IQ}}$ thus suffering from greater degradation than the TM-system. In figure 3 this is shown by comparing the mean squared error (MSE) of the initial channel

estimation for both systems at a SNR of $E_b/N_0 = 10$ dB. The higher the load β the larger the influence of $\tilde{\mathbf{n}}_{X,\mathrm{IQ}}$ gets.
Even though the IQ-system provides a worse initial estimation this estimation is still good enough to ensure convergence of the SIC iterations.

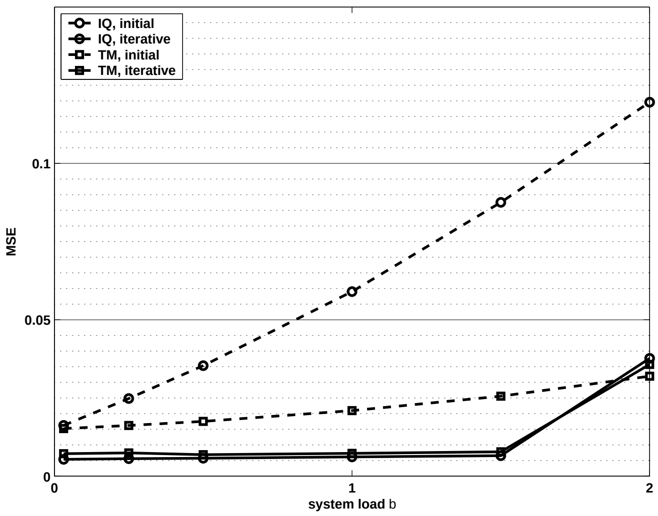

Figure 3. Mean squared error of initial channel estimation for different loads β for $E_b/N_0 = 10$ dB

3.2 Successive Interference Cancellation

The successive interference cancellation comprises U single user detectors. Users are sorted according to their power level. For the uth user ($1 \leq u \leq U$) interference for users 1 to $u-1$ determinded at the current iteration step as well as interference for users $u+1$ to U estimated at the previous iteration step are subtracted [10]. The coded bits $\hat{\mathbf{b}}_u$ are then detected by a single user detector and $\hat{\mathbf{d}}_u$ is derived by a FEC decoder processing soft values (SISO decoder). Following this step, $\hat{\mathbf{d}}_u$ is used to soft-reconstruct the received signal in order to determine interference caused by user u. This interference estimation is then used to detect users $u+1$ to U in the same iteration as well as users 1 to $u-1$ in the next iteration step. Due to the decoding gain as well as updated channel estimation the users' bit error rate can be improved in each iteration.
The mean squared error of the iteratively improved channel estimation is as well shown in figure 3.
Detection is only performed on the data part of the signal, i.e. with $\mathbf{r}$ consisting of a training period $\mathbf{r}_T$ and a data period $\mathbf{r}_I$ only $\mathbf{r}_I$ is considered. For the TM-system, this results in neglecting the preceding training part $\mathbf{r}_T$ of $\mathbf{r}$. For

the IQ-system, $\mathbf{r}_T$ contains as well data as training information. The known training information is removed from those symbols leaving the data in the real part thus reducing this part of $\mathbf{r}$ to BPSK symbols. The process of interference cancellation is schematically explained in figure 4.

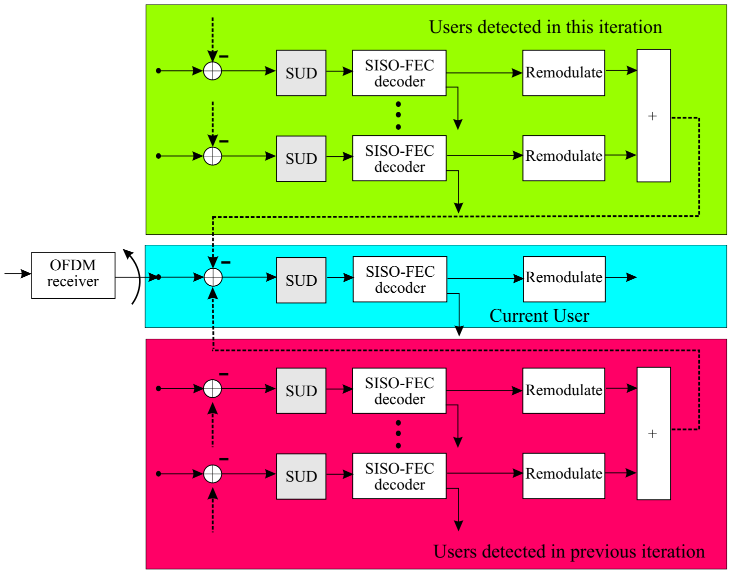

Figure 4. Successive Interference Cancellation

4. Simulation Results

In figure 5 bit error rates for both pilot setups are shown for loads of $\beta = 1$, $\beta = 1.5$ and $\beta = 2$. This corresponds to 32, 48 and 64 users. For $\beta = 1$, the IQ-system performs slightly better than the TM-system in the area between 3 and 8 dB. The gap between IQ- and TM-system is even greater for a load of $\beta = 1.5$. A load of $\beta = 2$ shows the largest performance gain. For a bit error rate of 10^{-3} the IQ-system gains 2 dB compared to the TM-system.
Even though the IQ-system starts with a worse initial channel estimation the iterative update of the channel estimate leads to similar results compared to the TM-system. The average number of iterations required for specific SNRs and different loads β are given in table 1.

However, the IQ-approach removes the training info prior to detection and thus reduces those symbols to BPSK. This applies to 70% of the symbols in an IQ-fading block. A reduction to BPSK corresponds to a reduction of the load by a factor of 2. This is mostly true when the SNR is still conciderably low. For a higher SNR both systems show equal performance since better

Table 1. Average Number of Iterations required for SIC

β	E_b/N_0 in dB	Av. Iter. (TM)	Av. Iter. (IQ)
1	7	13.2	10.4
1.5	9	12.49	11.03
2	13	16	12.5

channel estimation allows better removal of the multi-user interference for the TM-system as well.

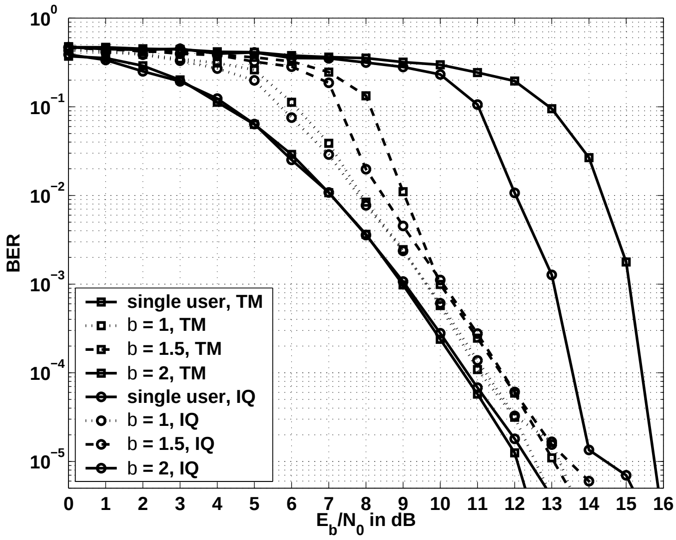

Figure 5. BER performance for the TM- and IQ-system with $L_f = 20$ and different loads β

5. Conclusion

In this paper two systems with different multiplexing schemes for pilot data have been compared. While the TM-system uses preceding QPSK training symbols the IQ-system maps the training information on the imaginary part of a subset of QPSK symbols. Both systems are processed by a combined ML channel estimation and a successive interference cancellation. Even though affected by a worse initial channel estimation the IQ-system shows better bit error performance due to a load reduction since 70% of it's QPSK symbols only carry information in the real part thus suffering by less multi-user interference. The performance gain compared to the TM-system is the better the higher the load β gets. Especially for high loads ($\beta = 2$) the gain of performance is as high as 2 dB.

6. Affiliations

The authors are with the Department of Communications Engineering, Universität Bremen, P.O. Box 33 04 40, D-28334 Bremen, Germany. Email: {feuersaenger,kuehn,kammeyer}@ant.uni-bremen.de

References

[1] Stefan Kaiser, *Multi-Carrier CDMA Mobile Radio Systems – Analysis and Optimization of Detection, Decoding and Channel Estimation*, Ph.D. thesis, German Aerospace Center, VDI, January 1998.

[2] A. Dekorsy and K.D. Kammeyer, "A new OFDM-CDMA Uplink Concept with M-ary Orthogonal Modulation," *European Transactions on Telecommunications (ETT)*, vol. 10, no. 4, pp. 377–390, July/August 1999.

[3] S. Moshavi, "Multi-User Detection for DS-CDMA Communications," *IEEE Communications Magazine*, pp. 124–136, October 1996.

[4] S. Verdu, *Multiuser Detection*, Cambridge University Press, New York, 1998.

[5] L.B. Nelson and V. Poor, "Iterative Multiuser Receivers for CDMA Channels: An EM-based Approach," *IEEE Trans. on Communications*, vol. 44, no. 12, pp. 1700–1710, December 1996.

[6] M.C. Reed, C.B. Schlegel, P.D. Alexander, and J.A. Asenstorfer, "Iterative Multiuser Detection for CDMA with FEC: Near-Single-User Performance," *IEEE Trans. on Communications*, vol. 46, no. 12, pp. 1693–1699, December 1998.

[7] P.D. Alexander, M.C. Reed, J.A. Asenstorfer, and C.B. Schlegel, "Iterative Multiuser Interference Reduction: Turbo CDMA," *IEEE Transactions on Communications*, vol. 47, no. 7, pp. 1008–1014, July 1999.

[8] M. Kobayashi, J. Boutros, and G. Caire, "Successive Interference Cancellation with SISO Decoding and EM Channel Estimation," *IEEE Journal on Selectes Areas in Commununications*, vol. 19, no. 8, pp. 1450–1460, August 2001.

[9] A. Lampe and J. Huber, "Iterative Interference Cancellation for DS-CDMA Systems with High System Loads Using Reliability-Dependent Feedback," *IEEE Trans. on Vehicular Technology*, vol. 51, no. 3, pp. 445–452, May 2002.

[10] V. Kühn, "Iterative Interference Cancellation and Channel Estimation for Coded OFDM-CDMA," in *IEEE International Conference on Communications (ICC)*, Anchorage, Alaska, USA, May 2003.

[11] 3GPP, "Physical channels and mapping of transport channels onto physical channels (FDD)," Tech. Rep. 3GPP TS 25.211 V5.3.0, 3rd Generation Partnership Project, Sophia Antipolis, France, December 2002.