OPTIMIZED CHANNEL CODING SCHEMES FOR A GUARD PERIOD FREE TRANSMISSION SYSTEM

Klaus Hueske, Jürgen Götze

University of Dortmund
Information Processing Lab
Otto-Hahn-Str. 4, 44221 Dortmund
klaus.hueske@uni-dortmund.de

Christian Vincent Sinn

University of Sydney
Telecommunications Laboratory
Sydney, Australia

ABSTRACT

Guard periods are widely used to avoid inter block interference in wireless communication systems. The independent processing of each data block enables computational efficient data estimation, however, the necessary insertion of guard periods produces a transmission overhead and reduces the throughput of the respective transmission system. By using overlapping techniques a block-wise data estimation can be realized without using guard periods. With this modification, either the throughput of the system can be increased or the code rate of the forward error correction code can be reduced. Based on the latter option we will propose two optimized channel coding schemes for the overlapping based system. The first uses a reduced code rate while the second exploits the characteristic error distribution of the overlapping based data estimator. The bit error performance of the resulting transmission systems is finally compared to a common cyclic prefix based transmission system.

Index Terms— data estimation, cyclic prefix, block processing, overlapping, channel coding

1. INTRODUCTION

Block transmission systems are often used to enable high data rate transmissions over dispersive wireless channels at reasonable computational costs. The block structure is realized by inserting guard periods into the data vector, which prevents inter block interference (IBI) caused by the channel convolution [1]. The avoidance of IBI enables data estimators with low complexity, as all data blocks can be processed independently.

However, the insertion of guard periods into the data vector reduces the throughput of the transmission system, as no data can be transferred during these periods. For example in the WLAN standard 802.11a [2], 20% of the total transmission time is allocated for guard periods.

By using an overlapping estimation scheme [3], we can combine the advantages of block processing and the avoidance of guard periods. This is realized by estimating the received data block-wise, accepting that the IBI will corrupt the estimated data. The resulting error distribution has a bathtub-like shape. Thus, the equalization error can be reduced by using only the middle, less corrupted part of the estimated block, while omitting the more erroneous outer parts. Applying this to consecutive overlapping blocks will result in an efficient block-wise data estimation at a reasonable remaining error level.

The avoidance of guard periods offers two options: The data throughput of the system can be increased or the code rate of the forward error correction (FEC) code can be decreased to improve the error correction performance. In the next sections we will compare three different systems: A common cyclic-prefix based system, an overlapping based system with reduced code rate and an overlapping based system with an optimized coding scheme. The latter will exploit the error distribution of the overlapping estimator, i.e. a lower code rate is used in the outer more erroneous parts.

The paper is organized as follows: In Section 2, the underlying data model will be described and an overlapping estimation scheme is derived. In Section 3, different coding schemes for the overlapping based systems will be discussed. The performance of these coding schemes in terms of bit error rate (BER) is evaluated in Section 4. Final conclusions are drawn in Section 5.

2. OVERLAPPING BLOCK PROCESSING

2.1. Data Model

The model describes the transmission of a data vector $\boldsymbol{d} \in \mathbb{C}^V$ of length V over a time dispersive wireless channel, which is described by its discrete impulse response $\boldsymbol{h} \in \mathbb{C}^L$ of length L. The channel is assumed to be time invariant during the transmission of the data vector $\boldsymbol{d}$. Noise effects are considered by adding a noise vector $\boldsymbol{n}$, which is obtained by sampling a white Gaussian noise process with power σ^2. The received vector $\boldsymbol{x} \in \mathbb{C}^{V+L-1}$ can be computed by convolution of the data vector $\boldsymbol{d}$ with the impulse response $\boldsymbol{h}$. By using the chan-

1-4244-1484-9/08/$25.00 ©2008 IEEE

nel convolution matrix $\boldsymbol{H} \in \mathbb{C}^{(V+L-1)\times(V)}$ the model can be summarized in

$$\boldsymbol{x} = \boldsymbol{H}\boldsymbol{d} + \boldsymbol{n}. \tag{1}$$

The receiver has to compute an estimate $\hat{\boldsymbol{d}}$ of the transmitted data $\boldsymbol{d}$. It is assumed that the received vector $\boldsymbol{x}$, the channel impulse response $\boldsymbol{h}$ and an estimate of the noise power σ^2 are known at the receiver. The transmitted data is uncorrelated and has a mean power of $\sigma_d^2 = 1$, therefore the MMSE (Minimum Mean Square Error) estimate of the transmitted data is given as

$$\hat{\boldsymbol{d}}_{MMSE} = (\boldsymbol{H}^H\boldsymbol{H} + \sigma^2\boldsymbol{I})^{-1}\boldsymbol{H}^H\boldsymbol{x}. \tag{2}$$

The direct computation of Equation (2) is hardly feasible for long data vectors, due to the high demand on computing power, storage requirements and large processing delay time. By periodically inserting guard periods of length $L-1$ into the data vector the channel convolution matrix $\boldsymbol{H}$ can be split-up into smaller submatrices $\boldsymbol{H}_B$, which can be processed independently and therefore reduce the complexity of the MMSE estimator.
In case of using a cyclic prefix as guard period [3] the resulting block matrices of size $B \times B$ with $B \ll V$ have a circular structure. This allows the use of FFT-based (Fast Fourier Trasform) EVD algorithms (Eigenvalue Decomposition) to compute Equation (2) efficiently. With $\boldsymbol{H}_B = \boldsymbol{F}^{-1}\boldsymbol{\Lambda}\boldsymbol{F}$ the EVD of $\boldsymbol{H}_B$ the block MMSE estimator can be denoted by

$$\hat{\boldsymbol{d}}_{MMSE,B} = \boldsymbol{F}_B^{-1}(\boldsymbol{\Lambda}^H\boldsymbol{\Lambda} + \sigma^2\boldsymbol{I})^{-1}\boldsymbol{\Lambda}^H\boldsymbol{F}_B\boldsymbol{x}_B, \tag{3}$$

with $\boldsymbol{F}$ the Fourier matrix and $\boldsymbol{\Lambda}$ a diagonal matrix containing the eigenvalues of $\boldsymbol{H}_B$. The resulting CP-SC (Cyclic Prefix Single Carrier) transmission system [4] is used as a reference in this paper. A similar processing structure is also used in CP-OFDM multi carrier systems [5].

2.2. Overlapping Data Estimation

In the previous section a block structure was obtained by inserting guard periods into the data vector. What happens if we omit the guard periods and still perform block-wise data estimation in the receiver? The resulting IBI will corrupt the estimated data. However, due to the finite channel length we can expect that the distorting influence of the neighbouring blocks is more significant in the border parts of the estimated blocks [3]. To verify this, the ensemble-averaged estimation error for three neighbouring blocks is depicted in Figure 1 (a). This bathtub like error distribution can be exploited by using overlapping data blocks instead of neighbouring blocks, i.e. a block with elements $n, ..., n+B$ is followed by a block $n+B-2D, ..., n+2B-2D$, as depicted in Figure 1 (b). Here B denotes the block length and $2D$ describes the length of the overlapping parts. The estimation error can then be reduced by omitting the overlapping, more erroneous outer parts of each block and keeping the middle parts for further

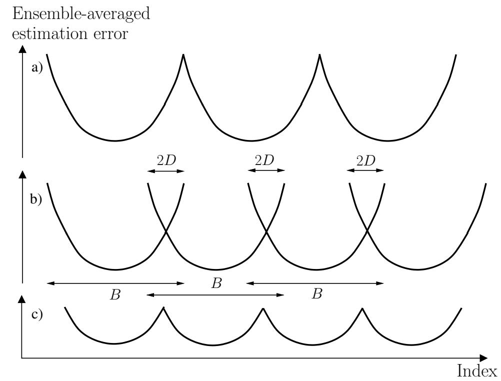

Fig. 1. Error distribution for overlapping data estimation.

processing. The resulting ensemble-averaged estimation error is depicted in Figure 1 (c).
To allow the use of efficient FFT based EVD algorithms for solving the MMSE equation (3), the overlapping block matrices are cyclically extended. This also means that the underlying signal processing structure is similar to known CP-OFDM systems. The overlapping estimation scheme is illustrated in Figure 2.

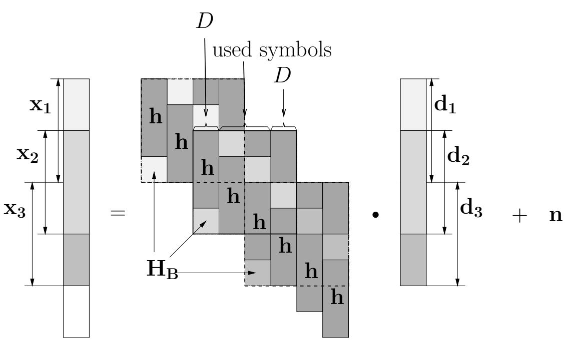

Fig. 2. Data estimation with overlapping submatrices.

3. CODING SCHEMES FOR OVERLAPPING ESTIMATION

As already mentioned, the use of guard periods reduces the throughput of the transmission system as no data can be transmitted during the guard periods. If the symbol rate of the transmission system is one, the data rate can be described by

$$R_d = \frac{B}{B+CP} = \frac{1}{1+\frac{CP}{B}}, \tag{4}$$

where B denotes the data block length and CP denotes the cyclic prefix length. If we also use an FEC code in the transmission system, the resulting data rate is further decreased by the code rate R_{CP}, which leads to a data rate of

$$\overline{R} = \frac{R_{cp}}{1+\frac{CP}{B}}. \tag{5}$$

The rate $\overline{R}$ describes the total "code rate" of the cyclic prefix based transmission system.
In case of overlapping estimation no guard periods are required, i.e. the data rate of the coded system is determined by the code rate R_{ov} of the used channel code. Assuming that both systems, the cyclic prefix based and the overlapping based, have identical data rates, it can be noted that $R_{ov} = \overline{R} < R_{cp}$. This means, the symbols that are saved by avoiding the cyclic prefix can be used for additional redundancy to increase the performance of the FEC code.
We can further exploit the characteristic error distribution of the overlapping based equalizer by assigning different code rates to different parts of the data block. This approach is shown in Figure 3, with R_h the higher code rate for the less erroneous parts and R_l the lower code rate with better error correction performance for the outer parts. To obtain identical

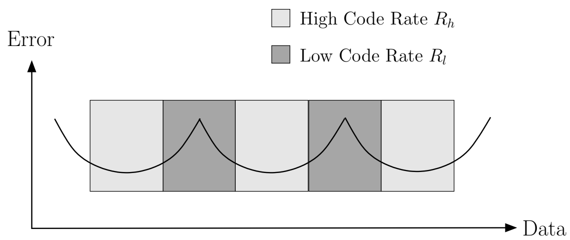

Fig. 3. Optimized coding scheme for overlapping estimation.

data rates for the systems, the code rates must fulfill

$$\frac{R_l B_l + R_h B_h}{B_l + B_h} \stackrel{!}{=} \overline{R}, \tag{6}$$

where B_l and B_h denote the length of the parts coded with lower code rate and higher code rate, respectively.

4. SIMULATION RESULTS AND COMPLEXITY

4.1. Simulation model

The performance of the different coding and estimation schemes is evaluated by using BER simulations. The systems to be compared are depicted in Figure 4.
The gray highlighted processing blocks are identical in all systems, i.e. channel coding, puncturing (P), interleaving (I), channel (H), MMSE estimator, deinterleaving (I^{-1}), depuncturing (P^{-1}) and channel decoding. The modulation scheme is chosen as BPSK (Binary Phase Shift Keying). For simulations, a convolutional code with constraint length $K = 3$ and code rate $R = 1/2$ in combination with a soft decision Viterbi decoder is used [6]. In general however, all kinds of channel codes (e.g. Turbo Codes or Block Codes) can be used. The required different code rates are obtained by puncturing, i.e. coded bits are periodically deleted before transmission to obtain a higher code rate [6]. Suitable puncturing patterns for the used code rates can be found in [7]. Furthermore a time

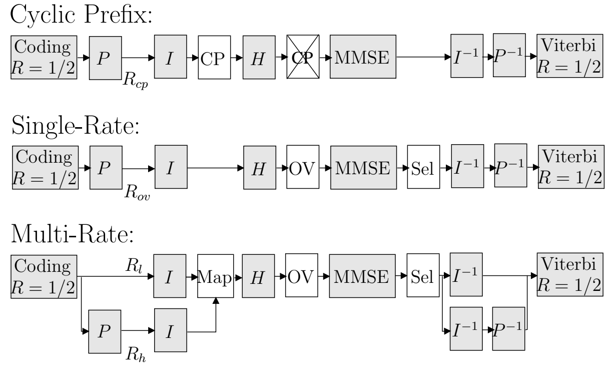

Fig. 4. Systems employing different coding schemes.

variant multi path channel with superposed white Gaussian noise and $L = 17$ taps is used. A detailed description of the channel model can be found in [8].
Cyclic-prefix reference system:
The data vector $\boldsymbol{d}$ is divided into blocks of length $B = 64$. Before transmission, each data block is extended with a cyclic prefix of length $CP = L - 1 = 16$. The cyclic prefix is removed before data estimation. The used code rate is $R = 2/3$, which leads to a data rate of $\overline{R} = 8/15$, following Equation (5). The parameters are examples taken from the WLAN standard [2].
Single-rate overlapping system:
The cyclic prefix insertion/deletion tasks are replaced by overlapping (OV) and selection (Sel). OV extracts overlapping blocks of size $B = 64$ with overlapping length $D = 11$. The selected parameters display a trade-off between remaining error level and number of required computations. After MMSE estimation only the inner part of the estimated data block is selected (Sel) and forwarded to the next processing unit. The code rate is chosen to be $R_{ov} = \overline{R} = 8/15$.
Multi-rate overlapping system:
To exploit the characteristic error distribution of the overlapping system, two different coded data streams with rate R_h and R_l are generated. The data is then mapped to the corresponding parts of the data stream, parts with high code rate to the inner parts and parts with lower code rate to the outer parts. To fulfill Equation (6), the code rates are chosen to be $R_l = 1/2$ and $R_h = 3/5$.

4.2. Simulation results

The BER performance of the different systems is shown in Figure 5. Due to the lower code rate the overlapping based systems perform significantly better than the cyclic prefix reference system over a wide range. The remaining estimation error, which is caused by IBI, leads to an error floor for high E_b/N_0 values, which is negligible for most applications.
The multi-rate system shows a lower error floor than the single rate system. This is caused by a higher error correction

performance of the channel code used for the outer parts. However, the implementation efforts are higher for the multi-rate system, due to additional multiplexing and mapping.

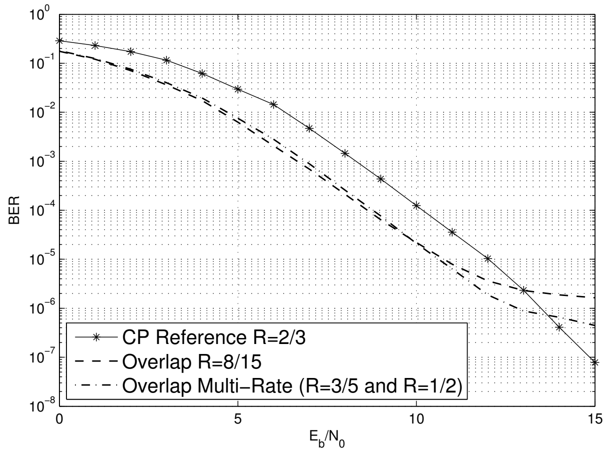

Fig. 5. BER of systems using different coding schemes.

4.3. Complexity

Considering Equation (3), the complexity of the estimator is dominated by the FFT and the inverse FFT. With $\frac{N}{2}\log_2 N$ the number of complex multiplications necessary to compute one FFT, the total number can be calculated by

$$M_{cp} = 2\frac{V}{B}\frac{B}{2}\log_2 B = V\log_2 B. \quad (7)$$

Due to the overlap in the systems without cyclic prefix, more data blocks have to be processed, so the total number of operations in the overlapping systems is given by

$$M_{ov} = 2\frac{V}{B-2D}\frac{B}{2}\log_2 B. \quad (8)$$

The complexity of the estimator is therefore increased by a factor

$$f = M_{ov}/M_{cp} = \frac{B}{B-2D}, \quad (9)$$

which is a factor of $f = 1.52$ for our example with $B = 64$ and $D = 11$.

An alternative way to reduce the overhead caused by cyclic prefixes is the use of longer data blocks. But besides the increased storage requirements and processing delay, which is a major drawback for real time mobile communication systems, the computational complexity will also increase.

Assuming a longer block length $B' > B$, the complexity of the system using longer blocks is increased by a factor

$$g = M'_{cp}/M_{cp} = \frac{\log_2 B'}{\log_2 B}. \quad (10)$$

For a block length of $B' = 1024$, for example, the number of required operations will be increased by $g = 1.66$.

5. CONCLUSIONS

In this paper optimized coding schemes for an overlapping based data estimator were introduced. As the overlapping based systems do not require any guard periods, the code rate of the used channel code can be reduced without affecting the throughput of the transmission system. The comparison with a common CP-SC system showed a significantly reduced BER over a wide range of E_b/N_0 values for the guard period free systems. The remaining error floor is significant only for very low BER values, even with the simple codes used for simulations here. The complexity of the proposed estimator is slightly increased compared to the used CP-SC systems, but stays below the complexity of a system using longer blocks to reduce the overhead caused by the cyclic prefix.

6. REFERENCES

[1] Zhendao Wang and G.B. Giannakis, "Wireless multicarrier communications," *IEEE Signal Processing Magazine*, vol. 17, pp. 29–48, 2000.

[2] IEEE, "Std 802.11a part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications. High-speed physical layer in the 5 GHz band," Tech. Rep., 1999.

[3] C. V. Sinn and J. Götze, "Computationally efficient block transmission systems with and without guard periods," *Signal Processing, Elsevier North-Holland, Inc.*, vol. 87, no. 6, pp. 1421–1433, 2007.

[4] J. Tubbax, B. Come, L. Van der Perre, L. Deneire, S. Donnay, and M. Engels, "OFDM versus single carrier with cyclic prefix: A system-based comparison," in *Proceedings of 54th IEEE Vehicular Technology Conference, 2001. VTC 2001 Fall. IEEE VTS 54th*, 2001.

[5] R. van Nee and R. Prasad, *OFDM for Wireless Multimedia Communications*, Artech House Publishers, 2000.

[6] Shu Lin and Daniel J. Costello Jr., *Error Control Coding, 2. edition*, Pearson Prentice Hall, 2004.

[7] P. Frenger, P. Orten, T. Ottosson, and A. Svensson, *Multirate convolutional codes*, Tech. Rep. 21, Dpt. of Signals and Systems, Communication Systems Group, Chalmers University of Technology, Göteborg, Sweden, 1998.

[8] K. Ruttik, "A wideband radio channel model for simulation of chaotic communication systems," in *Proceedings of ECCTD*, Budapest, August 1997, pp. 302–305.