AVOIDANCE OF GUARD PERIODS IN BLOCK TRANSMISSION SYSTEMS

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ABSTRACT

To meet the requirement of efficient cancellation of inter symbol interference (ISI) in high data rate transmissions over time dispersive channels block based transmissions are often adopted. This is the case in orthogonal frequency domain multiplexing (OFDM), cyclic prefix based single carrier (CP-SC) and block transmissions with null guard periods (ZP-SC). Guard periods are inserted between the data blocks that lower the spectral efficiency significantly. In this article techniques are presented and analyzed that aim at omitting the guard periods in the afore mentioned systems without increasing the computational complexity significantly. One is the application of overlapping methods, another the reasonable selection of the block size, a third the usage of guard periods shorter than the initial ones. The techniques can be combined arbitrarily. They are applied in transmissions over a mobile vector channel and assessed in terms of bit error rate (BER), spectral efficiency and computational complexity.

1. INTRODUCTION

In high data rate transmissions over wireless channels with long delay spreads inter symbol interference (ISI) is a major limiting factor. Therefore transmission systems need to be identified that perform ISI cancellation without excessive consumption of the computational recourses processor power and storage. Furthermore the identified systems shall show low bit error rate (BER) and work in a spectral efficient fashion. The criteria which asses the systems quality are computational complexity, BER, and spectral efficiency. Usually a reasonable trade off need to be found.

An important concept that enables computational efficient cancellation of ISI is the separation of a data burst into data blocks. If guard periods between the data blocks are inserted the blocks can be processed independently. However, the guard periods cause a decreased spectral efficiency. Transmission systems that rely on this concept of data blocking are orthogonal frequency domain multiplexing (OFDM), cyclic prefix based single carrier (CP-SC) and single carrier based on block transmissions with null guard intervals [10, 17, 16, 13, 3, 5]. They are all applied or proposed in high data rate wireless communications. In the wireless LAN standards IEEE 802.12b and HiperLAN/2 CP-OFDM is selected as transmission system [4, 8]. Thereby the guard periods allocate 20% of one data burst.

In this article approximation techniques are proposed and investigated that can omit the overhead of the guard periods without increasing the computational complexity excessively. For that purpose a mathematical model is adopted that describes the mentioned transmission system with and without applying approximation techniques by a set of equations. The computational complexity of the transmission systems applying the presented approximation techniques is in a similar dimension as the initial ones while the BER of the systems is increased. However, there are three concepts to lower the BER. These are a larger block size, the application of overlapping techniques, and the insertion of guard periods that are smaller than the initial ones. The techniques are assessed in terms of BER, spectral efficiency, and complexity.

The paper is organized as follows: After introducing the importance of data blocking and transmission systems that use these concept in chapter 2, approximation methods that can avoid the guard periods between subsequent blocks are presented and assessed in chapter 3. In chapter 4 the techniques are applied in a transmission over a wireless channel and assessed in this environment in terms of the BER. Conclusions are drawn in chapter 5.

2. BLOCK TRANSMISSION SYSTEMS

2.1. Data Model

We focus on burst structured, single-in single-out, high data rate transmissions over time dispersive channels. Here a digital, synchronous, baseband model is adopted. The data to be transmitted are gathered in the data vector $\mathbf{d} \in \mathbb{C}^B$. In the case of BPSK modulation d_b is either 1 or -1 with equal probability. During the transmission of one burst $\mathbf{d}$ the channel impulse response (CIR) $\mathbf{h} \in \mathbb{C}^L$ is assumed to be time invariant. A new CIR is computed in the next burst to account for the time varying nature of the channel. Thus the CIR during one data burst is modeled as finite impulse response (FIR) filter. The convolution of the data and the channel can be computed by multiplying the channel convolution matrix $\mathbf{H} \in \mathbb{C}^{B+L-1\times B}$ by $\mathbf{d}$. The received vector $\mathbf{x} \in \mathbb{C}^{B+L-1}$ is obtained by adding the noise vector $\mathbf{n} \in \mathbb{C}^{B+L-1}$ to the convolution:

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

The system of equations 1 is the model to be analyzed subsequently. A receiver has to compute the transmitted data $\mathbf{d}$ from the received data $\mathbf{x}$ and the CIR $\mathbf{h}$. In this article perfect knowledge of the CIR is assumed. The entries of $\mathbf{n}$ are realizations of a white Gaussian noise process, which models co-channel interference and noise. The data burst $\mathbf{d}$ is obtained by solving the system of equations 1. Since it is usually overdetermined and we do not know the particular realization of the noise $\mathbf{n}$ it has generally no solution. An approximated solution can be found by minimizing the energy of the noise. This is known as the least squares (LS) solution:

$$\min_{\hat{\mathbf{d}}_{LS}} \|\mathbf{x} - \mathbf{H}\hat{\mathbf{d}}_{LS}\|_2 \quad \rightarrow \quad \hat{\mathbf{d}}_{LS} = \underbrace{(\mathbf{H}^H\mathbf{H})^{-1}\mathbf{H}^H}_{\mathbf{H}^{\#}}\mathbf{x} \in \mathbb{C}^B.$$

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The least squares estimates $\hat{\mathbf{d}}_{LS}$ of the data $\mathbf{d}$ are obtained by multiplying the pseudo inverse $\mathbf{H}^{\#} \in \mathbb{C}^{B \times B+L-1}$ by the received vector $\mathbf{x}$. There are several methods to compute the LS-estimates efficiently, e.g., the QR decomposition by using Givens or hyperbolic rotations, the Cholesky algorithm, the Levinson-Durbin algorithm [6, 9, 14, 15]. Thereby the band and Toeplitz structure of the channel matrix is exploited to a certain degree. Independently of the selected algorithm the computational complexity to compute the LS-estimates increases with the size of the convolution matrix $\mathbf{H}$. Furthermore the whole received data vector need to be stored. The computational complexity necessary to compute the LS-estimates borders the data rate in a transmission system. To enable high data rate transmissions a concept that decreases the size of the channel matrix and thus the consumption of computational resources significantly is needed.

2.2. Data Blocking

The concept of data blocking leads to a reduced computational burden to solve the system of equations 1. The data burst $\mathbf{d}$ is divided into data blocks $\mathbf{d}_i \in \mathbb{C}^J$ with $J \ll B$. The data blocks are separated by guard periods which are at least as long as the maximum length of the CIR minus 1: $L-1$. In this way inter block interference (IBI) is eliminated. This is reflected in the data model: The large system of equations 1 is divided into a set of significantly smaller systems, which can be solved independently of each other. This method is sketched in figure 1. The guard periods can contain nulls, cyclic prefixes (CP) and pseudo-noise (PN) sequences, respectively. They are inserted either at the beginning or at the end of a block [16, 2, 13]. We restrict ourself to the case inserting zeros at the end of one block. Since the computational complexity to solve the system increases with the size of the channel matrix, data blocking provides a method to reduce the complexity enormously.

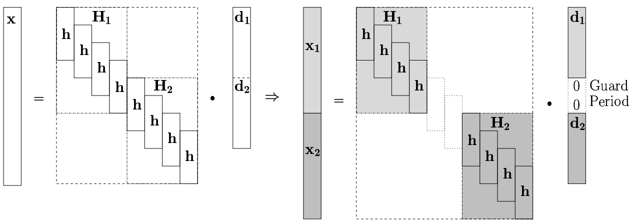

Fig. 1. Structure of equation system after data blocking and insertion of guard periods (zero pads).

This is an important concept that enables efficient data detection in high data rate transmissions over time dispersive channels without excessive consumption of computational resources (storage, processor power). The major drawback results from the insertion of guard periods. They are inserted at the transmitter, which means that they are bandwidth consuming. A larger block size would decrease the bandwidth consuming influence from the guard period. However, it would require more computational resources.

2.3. Transceiver Processing

Next it is focused on solving the subsystems (see figure 1)

$$\mathbf{x}_i = \mathbf{H}_i \mathbf{d}_i + \mathbf{n}_i, \qquad (2)$$
$$\mathbf{H}_i \in \mathbb{C}^{J+L-1 \times J}, \mathbf{x}_i, \mathbf{n}_i \in \mathbb{C}^{J+L-1}, \quad \mathbf{d}_i \in \mathbb{C}^J.$$

The matrix $\mathbf{H}_i$ is Toeplitz and band structured, which implies that $\mathbf{H}_i$ has always full column rank. The matrix $\mathbf{H}_i$ can only become rank deficient if $\mathbf{h} = \mathbf{0}$, which can not be the case in practice. Full rank of $\mathbf{H}_i$ implies that the pseudo inverse $\mathbf{H}_i^{\#} \in \mathbb{C}^{J+L-1 \times J}$ does always exist, independently of the values of the CIR. In the absence of noise the error free estimation of $\mathbf{d}_i$ is therefore guaranteed. This becomes obvious by applying the LS-criterion to estimate $\mathbf{d}_i$:

$$\hat{\mathbf{d}}_{i,LS} = \mathbf{H}_i^{\#}\mathbf{x}_i = \underbrace{\mathbf{H}_i^{\#}\mathbf{H}_i}_{=\mathbf{I}} \mathbf{d}_i + \mathbf{H}_i^{\#}\mathbf{n}_i = \mathbf{d}_i, \quad \text{if } \mathbf{n}_i = \mathbf{0}. \qquad (3)$$

A receiver that computes $\hat{\mathbf{d}}_{i,LS}$ for all i needs to compute the pseudo inverse $\mathbf{H}_i^{\#}$ one time per burst from the CIR and a matrix vector product per data block. Faster changing of the CIR would require updating of the pseudo inverse during a data burst. A transmission system that uses the concept of equation 3 is known as block transmission system with null guard intervals [1] or as ZP-only system in [16].

Further savings of computational complexity are obtained by exploiting the properties of a cyclic channel matrix: The vector $\mathbf{d}_{i,ZP} \in \mathbb{C}^{J+L-1}$ is obtained after appending $L-1$ zeros to $\mathbf{d}_i$. The corresponding matrix $\tilde{\mathbf{H}}_i \in \mathbb{C}^{J+L-1 \times J+L-1}$ is obtained by inserted columns at the right hand side of $\mathbf{H}_i \in \mathbb{C}^{J+L-1 \times J}$ in a fashion that a cyclic matrix is created. Thereby the received vector $\mathbf{x}_i$ remains unchanged: $\mathbf{x}_i = \tilde{\mathbf{H}}_i \mathbf{d}_{i,ZP} + \mathbf{n}_i$. The properties of the matrices $\mathbf{H}_i$ and $\tilde{\mathbf{H}}_i$ are heavily different. On contrast to $\mathbf{H}_i$ the cyclic matrix $\tilde{\mathbf{H}}_i$ is not guaranteed to have full column rank. Therefore the inverse $\tilde{\mathbf{H}}_i^{-1}$ might not exist. However, the computation of $\tilde{\mathbf{H}}_1^{-1}\mathbf{x}_i$ can be performed very efficiently, which is explained subsequently. The eigenvalue decomposition of $\tilde{\mathbf{H}}_i$ is given by

$$\tilde{\mathbf{H}}_i = \mathbf{F}^{-1}\mathbf{D}\mathbf{F}, \quad \mathbf{D} = \text{diag}\left(\mathbf{F}\tilde{\mathbf{H}}_i(:,1)\right).$$

The matrix $\mathbf{F} \in \mathbb{C}^{J+L-1 \times J+L-1}$ is the DFT matrix. It contains the eigenvectors of $\tilde{\mathbf{H}}_i$. A multiplication with $\mathbf{F}$ can be implemented by using FFT algorithms. The diagonal matrix $\mathbf{D} \in \mathbb{C}^{J+L-1 \times J+L-1}$ contains the eigenvalues, which are computed by transforming the CIR in the frequency domain. The inverse $\tilde{\mathbf{H}}_i^{-1}$ does not exist if at least one eigenvalue is zero. That is the case if the channel transfer function has a zero on the DFT grid. This can occur in time dispersive channels. The data vector $\mathbf{d}_i$ is estimated by:

$$\hat{\mathbf{d}}_{i,CP} = \tilde{\mathbf{H}}_i^{-1}\mathbf{x}_i = \underbrace{\tilde{\mathbf{H}}_i^{-1}\tilde{\mathbf{H}}_i}_{=\mathbf{I},\ \text{if } \mathbf{D}_{j,j}\neq 0\ \forall j} \mathbf{d}_i + \tilde{\mathbf{H}}_i^{-1}\mathbf{n}_i = \mathbf{d}_i,$$
$$\text{if } \mathbf{n}_i = \mathbf{0} \text{ and } \tilde{\mathbf{H}}_i^{-1} \text{ does exist.}$$

Transmission systems that uses a similar concept are OFDM and CP-SC [10, 17, 16, 13, 3]. Thereby cyclic prefixes are chosen as guard periods.

In the case of perfect knowledge of the CIR $\mathbf{h}$, no additive noise ($\mathbf{n} = 0$) and the existence of $\tilde{\mathbf{H}}_i^{-1}$ both presented data detection techniques, the pseudo inverse technique (PI) and the cyclic matrix inversion technique (CMI), render error free detection. If the noise is assumed to be nonzero the terms $\mathbf{H}_i^{\#}\mathbf{n}_i$ and $\tilde{\mathbf{H}}_i^{-1}\mathbf{n}_i$ describe the detection error. If $\tilde{\mathbf{H}}_i$ is singular $\mathbf{d}_i$ can not be detected, if it is close to singular the computation of $\tilde{\mathbf{H}}_i^{-1}\mathbf{n}_i$ results in enormous noise enhancement. A close to singular matrix is obtained if the channel suffers from deep fading on the DFT grid.

If the last two rows of the initial system of equations 1 are discarded the resulting system can be solved exactly and block wise by successive interference cancellation. In order to obtain this solution the square sub matrices must have full rank and the noise must be zero. The block wise technique is depicted in figure 2. First, $\mathbf{d}_1$ is computed from $\mathbf{x}_1$ and $\mathbf{h}$: $\mathbf{d}_1 = \mathbf{H}_{i,IC}^{-1}\mathbf{x}_1$.

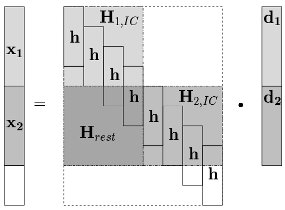

Fig. 2. Successive interference cancellation.

Then the inter block interference $\mathbf{H}_{rest}\mathbf{d}_1$ (see dark shadowed part of figure 2) is computed and subtracted from the second received block $\mathbf{x}_2$. The second data block $\mathbf{d}_2$ is computed from the interference eliminated data block $\mathbf{x}_{2,IC} = \mathbf{x}_2 - \mathbf{H}_{rest}\mathbf{d}_1$ and $\mathbf{h}$: $\mathbf{d}_2 = \mathbf{H}_{i,IC}^{-1}\mathbf{x}_{2,IC}$. Further blocks are computed in a similar fashion. This technique solves the reduced equation system in the absence of noise exactly. It results neither in the PI solution nor in the CMI solution of the system of equations 2. Information of the first data block $\mathbf{d}_1$ can be found in the first $B + L - 1$ values of $\mathbf{x}$. This is a larger block than $\mathbf{x}_1$. This can be reflected in a particularly poor condition of $\mathbf{H}_{i,IC}$ which can result in severe noise enhancement if $\mathbf{n}$ is not set to zero. Furthermore there is a risk of error propagation.

A further computational efficient technique to solve the large system 1 is the application of a linear equalization filter (FIR). Thereby the data is detected by multiplying the received vector $\mathbf{x}$ by a Toeplitz matrix $\mathbf{G}$ that contains the filter weight vector $\hat{\mathbf{g}}_F \in \mathbf{C}^M$:

$$\hat{\mathbf{d}}_F = \mathbf{G}\mathbf{x} = \underbrace{\mathbf{G}\mathbf{H}}_{\approx \mathbf{I}}\mathbf{d} + \mathbf{G}\mathbf{n}, \quad \mathbf{G} \in \mathbb{C}^{B+p \times B+L-1}.$$

The parameter p is the delay of the concatenation of the channel and the FIR filter. The vector $\hat{\mathbf{d}}_F$ contains the estimates of $\mathbf{d}$ delayed by p. The filter weight vector $\hat{\mathbf{g}}_F$ is computed from the perfect CIR by solving the zero forcing matrix equation that relates the CIR with the filter weights [7]: The convolution of the channel and the filter shall result in a vector containing a single one at an arbitrary position. Possibly no $\mathbf{g} \in \mathbb{C}^M$ can be found that fulfills the requirement, so that an error vector $\delta(\mathbf{p})$ is added. Minimizing the error's energy (least squares criterion) renders the filter coefficients:

$$\begin{aligned} \mathbf{H}_F\mathbf{g} = \mathbf{p} + \delta(\mathbf{p}) \quad &\Rightarrow \quad \mathbf{g} = \mathbf{H}_F^{\#}\mathbf{p} + \mathbf{H}_F^{\#}\delta(\mathbf{p}), \\ &\mathbf{H}_F \in \mathbb{C}^{M+L-1 \times M}, \\ \mathbf{p} = \begin{bmatrix} 0 & \dots & 1 & 0 & \dots & 0 \end{bmatrix}^T &\in \mathbb{C}^{M+L-1}, \\ &\hat{\mathbf{g}}_F = \mathbf{H}_F^{\#}\mathbf{p}. \end{aligned}$$

The computation can be implemented efficiently by solving a Cholesky down dating problem [14, 9, 6]. Since $\mathbf{H}_F^{\#}$ does always exist, $\hat{\mathbf{g}}_F$ can always be computed. However, perfect knowledge of the CIR and no additive noise does not guarantee perfect detection since the matrix product $\mathbf{GH}$ does only approximate the identity matrix $\mathbf{I}$. The quality of the approximation depends on the filter order M and the CIR to be equalized. The filtering, that is a multiplication by a Toeplitz matrix, can be implemented in the frequency domain by using overlap add or save techniques. Thereby a block wise processing is adopted. Notice that the overlap add/save method computes the exact filter output $\mathbf{Gx}$. However, the filter itself can only remove $\mathbf{H}$ approximately. The insertion of guard periods is performed at the receiver. Therefore it does not cause spectral efficiency loss. A transmission system applying this technique is called single carrier with frequency domain equalization (SC-FDE) [11, 7, 14]. Thereby similar receiver structures as in a CP-SC systems are obtained [14].

As already mentioned the bandwidth consuming insertion of guard periods is a major drawback of transmissions based on data blocking. In the following we present approximation techniques which retain the properties of the systems based on either the pseudo inverse (PI) or the cyclic matrix inversion (CMI) but can avoid the overhead of guard periods. Thereby the computational resources lie in a similar dimension as the initial system. The quality of the approximations is assessed by the mean square error of every symbol.

3. AVOIDANCE OF GUARD PERIODS

If data blocking is applied without introducing the guard periods an estimation error is obtained even if the noise is zero and the inverse $\tilde{\mathbf{H}}_i^{-1}$ does exist. The error results from inter block interference produced from the previous block and the time dispersive channel. It is a measure for the effect of not eliminating inter block interference by guard periods. The considered subsystems are depicted in figure 3. This technique is chosen as reference to assess

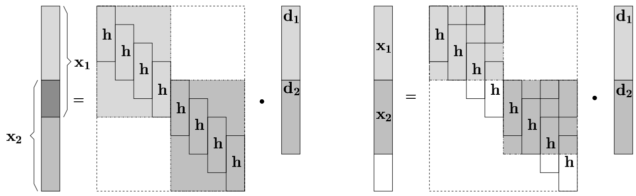

Fig. 3. Structure of equation system after data blocking without insertion of guard periods (zero pads).

the approximations. Since $\mathbf{H}_i$ and $\tilde{\mathbf{H}}_i$ remain unchanged the properties of the inverse cyclic matrix (CMI) and pseudo inverse (PI) and their effect on the transmissions remain unchanged as well. The quality of the estimates are assessed by an ensemble-averaged square error. It is plotted as a function of the symbol index in figure 5 (cases CMI-0-0 and PI-0-0). In the simulation the channel is of length $L = 5$. Each tap of the channel is equally distributed in the range of $[0, 1]$. The $\mathbf{d}$-vector contains a Bernoulli sequence, that is either 1 or -1, equally distributed. The noise $\mathbf{n}$ is set to zero. The block size is set to $J = 64$. The squared estimation error $\|\hat{d}_n - d_n\|_2$ is averaged over 25000 trails. Each contains a knew realization of the channel and the input data. Only system matrices with condition numbers lower than 100 are considered.

We observe that the estimation error varies with the symbol index. The distance between the maximum errors is equal to the block size. The largest error occurs at the beginning and at the end of a block, whereas the estimates in the middle of a block have a significantly lower error level. This holds for the pseudo inverse (PI) and the inverse of the cyclic matrix (CMI) based techniques.

To improve the data estimation without inserting guard periods we let the considered sub matrices overlap each other as shown in figure 4. After solving the subsystem we discard the estimates at

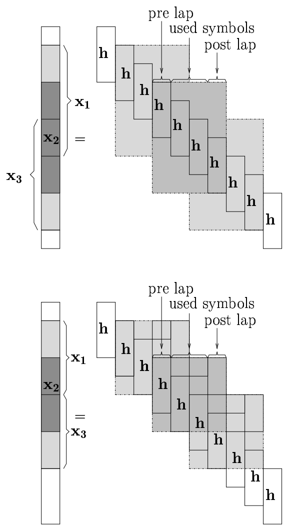

Fig. 4. Overlapping technique for pseudo inverse (PI) and cyclic matrix inversion (CMI).

the beginning (pre lap) and at the end (post lap) of the estimated block. In this way the worse estimates are discarded whereas the better ones are retained. Due to the overlapping every symbol is estimated on the better level. The computational complexity of this technique is by a factor $J/(J - L_{pre} - L_{post})$ larger than the reference, whereas storage requirements remain the same. In figure 5 the overlapping techniques are compared with the reference without overlapping for different pre- and post laps. The result provides

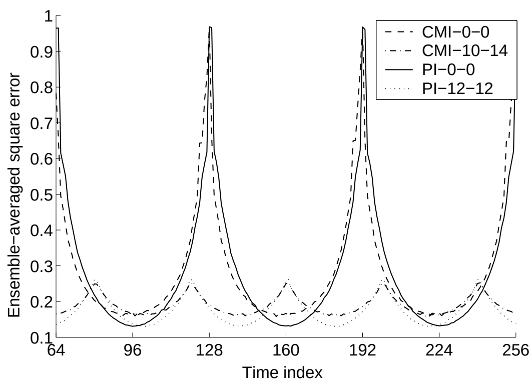

Fig. 5. Ensemble averaged square error of different detection techniques (PI, CMI) with different values of the pre and post lap as a function of the symbol index. The parameter in the legend are: selected technique - length of pre lap L_{pre} - length of post lap L_{post}.

a method to improve the quality of the approximation: The usage of pre- and post laps, which let the complexity increase by a factor of $J/(J - L_{pre} - L_{post})$. Another is to enhance the size of the considered sub matrices, which increases the complexity substantially stronger in dependence of the selected method to compute the estimated data block. Furthermore larger sub matrices imply larger storage requirements. Third, the insertion of guard periods that are shorter than the maximum length of the CIR can reduce the influence of IBI. However, this technique would cause a spectral efficiency loss but would not require extra computations. Next these techniques are applied to a transmission over a fast fading radio channel and are assessed in terms of BER.

4. TRANSMISSION SYSTEMS WITHOUT GUARD PERIODS

The transmission systems that result from either the CMI or PI method are considered subsequently. The channel is modeled as tap delay line filter of length L. Each tap is equally spaced by the symbol duration. The tap weights are approximately Rayleigh distributed. The maximum Doppler frequency is set 926Hz. The mean power of the taps is set to $\mathbf{q} = [0.1, 0.2, 0.5, 0.3, 0.1]$. Further explanations of the channel model can be found in [12].

The bit error rate (BER) is measured as a function of the signal-to-noise ratio (SNR) in the block based transmissions with and without guard periods. The results are depicted in figure 6. The PI

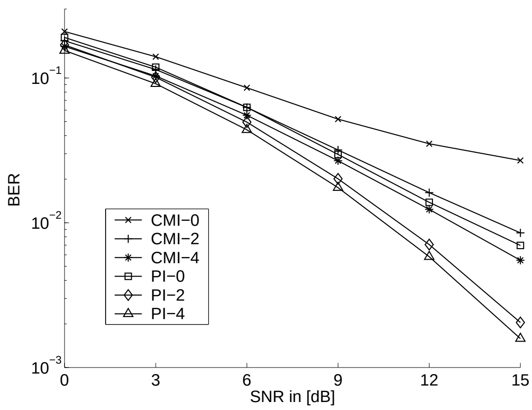

Fig. 6. BER of different detection techniques with different length of guard periods as a function of the SNR. The parameter in the legend are: transmission method - length of guard period. The block size is set to 64.

method performs significantly better than the CMI method. However, the CMI method requires less computational recourses.

Next the BER is measured for different values of the pre and post lap and for different block sizes in transmission systems without guard periods (see figure 7). A larger block size lowers the BER in the simulated systems.

5. CONCLUSIONS

In high data rate transmissions over wireless channels data blocking of a transmitted data burst is an essential technique to reduce computational complexity necessary to equalize the time dispersive channel. Transmission systems that rely on data blocking are OFDM, CP-SC and block transmission systems with null guard

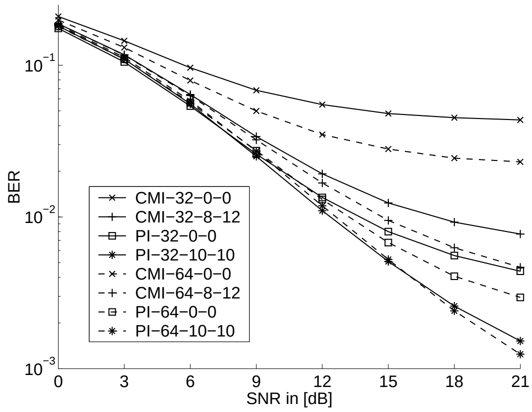

Fig. 7. BER of different detection techniques in transmission systems without guard periods as a function of the SNR. The parameter in the legend are: transmission method - block size - length of pre lap - length of post lap.

intervals. Thereby either a multiplication of data blocks by an inverse cyclic matrix or a pseudo inverse is computed. The different properties of matrices result in essential differences in terms of the BER of the resulting transmission systems. However, the block based techniques cause a large loss in spectral efficiency due to the insertion of guard periods between the blocks. In this paper techniques are presented that can omit the guard period without increasing the complexity excessively. The techniques are applied to transmissions over wireless channels. Thereby it turns out that three techniques can be adopted to reduce the BER. One is the application of overlapping, which enhances the computational complexity slightly. A second increases the size of the considered sub matrices, which let the complexity increase significantly. A third inserts guard periods, that are smaller than the initial ones. This result in a loss of spectral efficiency, but does not require much extra computations. Therefore techniques are identified to trade of the criteria spectral efficiency, complexity and BER in block based transmission systems that eliminate ISI efficiently.

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