A new scalable decoder for linear space-time block codes with intersymbol interference

Marc Kuhn, Armin Wittneben
University of Saarland, Institute of Digital Communications, D 66041 Saarbruecken, Germany
Email: marc.kuhn@LNT.uni-saarland.de , armin.wittneben@LNT.uni-saarland.de

***Abstract* - Space-Time Codes represent a key technology for future broadband wireless communication systems. In this paper a class of space-time block codes according to [1] is used which can lead to intersymbol interference (ISI) due to an optimized diversity performance. Therefore ISI compensation is an important task of the decoding process of these codes. Several known ISI compensation methods can be applied for example MMSE equalization or parallel or serial ISI cancellation.**

In this paper a new scalable ISI cancellation method is presented, that by using a posteriori information achieves almost the performance of the maximum likelihood decoder but with a much lower complexity. The key idea is to use estimated a posteriori probabilities to determine the order of the cancellation process. In each iteration the decoder jointly decodes a variable number of symbols, which meet a specified probability threshold. By varying the threshold, the decoder is scalable in such a way that the complexity of the decoder – and consequently the available data flow rate – can be adapted in a wide range to the requests of the transmission, to a given node complexity or a required quality of service.

I. Introduction

The statistical changes of the communication channel (fading) often found during the transmission of digital information can affect the average reliability of the information transmission for a given signal power. Space-Time codes combat these fading effects by utilizing the diversity of the communication channel given for example by the use of an antenna array at the transmitter and / or at the receiver [1], [2]. High rate space-time codes increase the data rate over Multiple Input Multiple Output (MIMO) channels without increasing the bandwidth by using the "spatial subchannels" which are available in rich diversity [1], [3], [4]. In this paper a special class of space-time codes according to [1] is used. One of the tasks of the decoder for these codes is the compensation of ISI, that can result from an optimized diversity performance and from interfering spatial subchannels [3], [4]. Because otherwise the performance could be heavily affected by the ISI.

In this paper a new interference cancellation method is presented using the ISI compensation of the employed space-time code as an example. On principal, this method can be used for other applications too.

The outline of the paper is as follows: in Section II the considered class of space-time block codes is described. The new ISI cancellation method is discussed in Section III and in Section IV simulation results are presented.

II. Space-Time Code

The linear space-time block codes according to [1] are highly flexible and adaptive. No a priori channel knowledge is required at the transmitter. Fig. 1 a) shows a system block diagram of the used linear space-time block code. Such a code consists of two concatenated but decoupled linear block codes, the inner code and the outer code.

The inner code is used for an adaptation to the applied number of transmit and receive antennas. Efficient code matrices can be used for transmit (TX) diversity and joint TX diversity and spatial subchanneling. The inner code is optimized with respect to the variation of the instantaneous channel capacity conceived by the outer code. The outer code is optimized for diversity performance and achieves a high diversity gain and an excellent performance in a fading environment even at code rate 1.

Due to the code concatenation the diversity performance optimization and channel conditioning (adaptation to the number of TX and RX antennas, pure TX diversity, pure spatial subchannels, joint subchanneling and TX diversity) are decoupled.

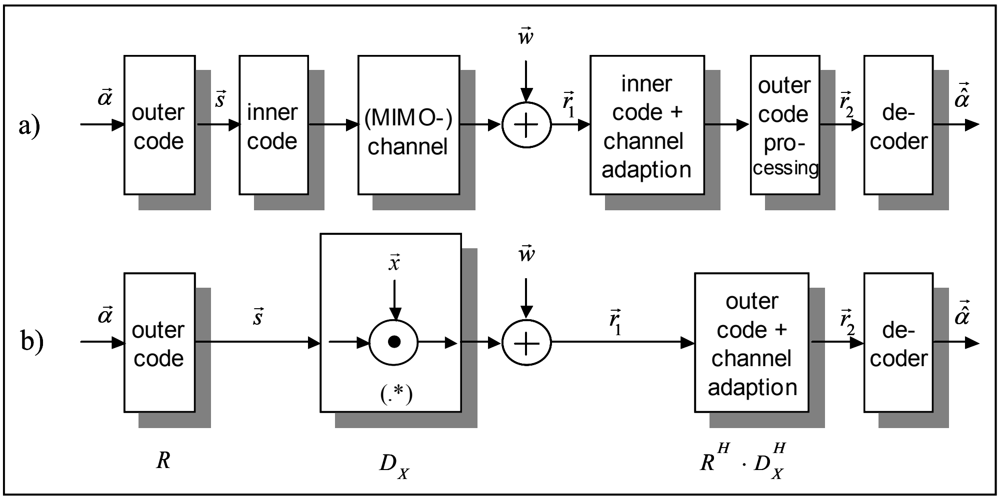

Fig. 1. Linear space-time block code

This class of space-time codes is very flexible, it is independent from the used modulation alphabet and can easily be adapted to the requests of the transmission, for example to different node complexities, subnet structures or transmission channels. Furthermore the use of a large block length is possible [1]. These properties will be very important for future heterogeneous broadband communication systems.

In the following a baseband representation according to Fig. 1 b) is used because the inner code is not in the focus of this paper. The inner code and the MIMO channel are modeled as a Rayleigh fading channel $\vec{x}$ under the assumption that fading is independent for every transmitted symbol ($\vec{x}$ is a sequence of statistically independent complex Gaussian random variables with zero mean and unit variance $E[|\vec{x}[k]|^2] = 1$). The outer code is represented by the code matrix R which is orthonormal

$$R^H \cdot R = I$$

where I is the unit matrix. The vector $\vec{\alpha}$ is the transmitted symbol vector, $\vec{w}$ contains the samples of the noise. The matrix D_x is a diagonal matrix of $\vec{x}$.

The received symbol vector $\vec{r}_2$ can be derived as follows:

$$\vec{r}_2 = R^H \cdot D_X^H \cdot D_X \cdot R \cdot \vec{\alpha} + R^H \cdot D_X^H \cdot \vec{w}$$

$$\vec{r}_2 = \Lambda_{ISI} \cdot \vec{\alpha} + \vec{n} \qquad (1)$$

The fading in D_x introduces ISI because the orthonormality of R is destroyed. The ISI included in the received signal is linear and represented by the matrix Λ_{ISI}. In Fig. 2 an example for the real part of such an interference matrix is shown for block length 32. To compensate this ISI a decoder using an equalization method is needed.

III. Interference Compensation

A maximum likelihood decoder is optimal for interference compensation but due to its high complexity it is in many cases not suitable for the practical use. Therefore only suboptimal methods are possible. These can roughly be classified in linear methods (for example zero forcing or MMSE detectors) and subtractive interference cancellation methods, which again can be divided in serial (successive) and parallel techniques. Subtractive interference compensation methods are already presented in many publications, for example a serial method in [3] and a parallel method in [5]. The serial method according to [3] first applies a linear equalization. Then the influence (interference) of an estimated symbol on the remaining symbols is compensated using the channel knowledge at the receiver. Then a linear equalization follows again before compensating the influence of the next estimated symbol. On

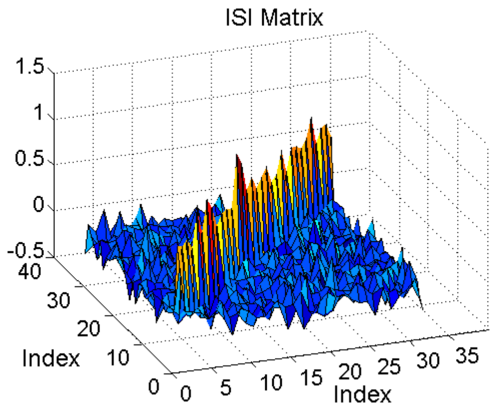

Fig. 2. Example of an ISI matrix (real part)

account of sequence errors the order of this cancellation process is important. In [3] the order is determined by a priori symbol error probabilities.

A. New scalable interference cancellation method

The interference compensation method presented in this paper is a combination of a parallel and a serial method. After a linear equalization a segment consisting of received symbols is parallel decoded in each iteration. This segment consists of a variable number of symbols, which have an a posteriori symbol error probability below a certain threshold. Than the ISI of the symbols of this segment is compensated using the knowledge of the channel. This is the key idea: to use estimated a posteriori probabilities to determine the order of the cancellation process. In the next iteration the a posteriori symbol error probabilities of the remaining symbols of the received block once more are estimated. Based on these values the next segment of symbols is determined. The complexity of the decoder can be adapted in a wide range by choosing a particular threshold.

Algorithm: Interference compensation of a received block of symbols:

1. MMSE estimation of all symbols in consideration of the interference matrix
2. Determining the a posteriori error probabilities of all still not decoded symbols on the basis of the MMSE estimations
3. Determining the segment of the symbols that will be jointly decoded on the basis of the a posteriori error probabilities
4. Deciding the symbols of the segment of step 3
5. Compensation of the interference of all symbols of step 4 on the remaining not decoded symbols

Then step 1 follows again; only not decoded symbols will be taken into account. These steps are repeated until all symbols are decoded.

In Fig. 3 this compensation process is shown for the considered space-time codes. The received symbol vector $\vec{r}_2$ is multiplied with the MMSE matrix $G^{(1)H}$. This matrix is calculated using the knowledge of Λ_{ISI} and σ_n^2 and employing the mean squared error (MMSE) criterion to minimize

$$\min\{ \vec{e} = G^{(1)H} \cdot \vec{r}_2 - \vec{\alpha} \} .$$

The elements of vector $\vec{d}^{(1)}$ are MMSE estimations of all symbols. For all these estimated values the a posteriori symbol error probabilities are calculated.

The a posteriori error probability of a received 2-PSK symbol is

$$P_{e,2-PSK} = (1 + \exp(\frac{1}{\sigma_n^2} \cdot 2 \cdot |d| \cdot \sqrt{E_b}))^{-1} \quad (2)$$

where σ_n^2 is the variance of the noise after MMSE equalization (assumed as AWGN), $|d|$ is the absolute value of the estimated amplitude of the symbol and $s_1 = - s_2 = \sqrt{E_b}$ are the two possible signal points, E_b is the energy per bit [6].

In the case of the space-time codes according to [1] the a posteriori symbol error probabilities can be approximated under the assumption of additive white Gaussian noise (AWGN), although the noise is colored.

4-QAM can be viewed as two 2-PSK signals I and Q (in phase and quadrature component) with statistically independent noise and independent error probabilities. Then the a posteriori error probability for a 4-QAM symbol can be approximated as:

$$\begin{aligned} P_{e,4-QAM} &= (1 - \bar{P}^{(I)}_{e,2-PSK} \cdot \bar{P}^{(Q)}_{e,2-PSK}) \\ &= P^{(I)}_{e,2-PSK} + P^{(Q)}_{e,2-PSK} - P^{(I)}_{e,2-PSK} \cdot P^{(Q)}_{e,2-PSK} \end{aligned} \quad (3)$$

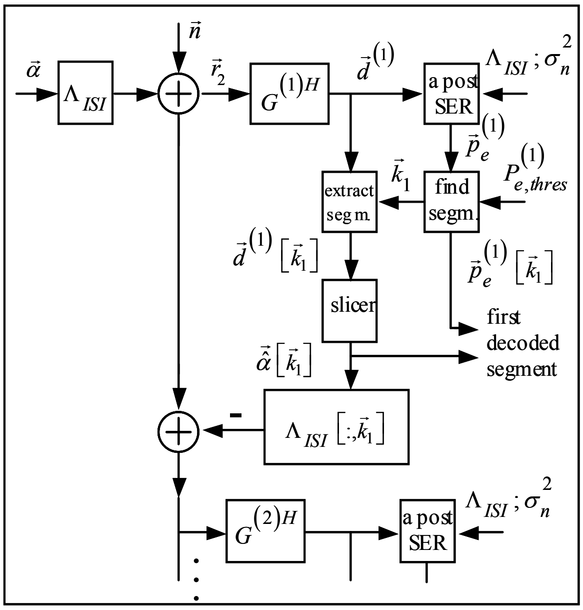

Fig. 3. Interference compensation process

After calculating these probabilities a segment $\vec{d}^{(1)}[\vec{k}_1]$ of estimated symbols is parallel decoded (simultaneously sliced). This segment consists of a variable number of symbols with an a posteriori symbol error probability below a certain threshold $P_{e,thres}^{(1)}$. If all symbols have an error probability higher than this threshold, then only the symbol with the lowest error probability is decoded. After that the ISI of these decoded symbols concerning the remaining symbols is canceled using the knowledge of Λ_{ISI}.

The next iteration starts with the calculation of the MMSE matrix $G^{(2)H}$ and the estimation of the remaining symbols and their a posteriori probabilities. This process stops when all received symbols are decoded.

Various refinements of the interference compensation process are conceivable e. g. an optimal choice of the decoder threshold value in each iteration or successive forward-backward iterations, if in any intermediate step the best estimated a posteriori symbol error probability is above the threshold. Moreover the a posteriori symbol error probabilities are available for further use at the receiver, e. g. as soft decisions for additional FEC coding / decoding.

IV. Results

In this section results are presented based on simulations using the outer code according to [1] in a Rayleigh fading environment (Fig. 1 b)). Perfect channel knowledge at the receiver is assumed. The decoder (Maximum a posteriori DFE – MAP-DFE) uses the new ISI cancellation method.

Fig. 4 and Fig. 5 highlight the efficiency of the new decoder. They show the symbol error rate (*SER*) of 4-QAM versus E_b / N_0 at the receiver for a Rayleigh fading channel and block length 20 ($\vec{r}_2$ consists of 20 elements) and block length 32 respectively. Besides they show the performance of 4-QAM for an AWGN channel as a reference. The decoder threshold is zero that means only the symbol with the lowest a posteriori error probability is decoded in each iteration. The new decoder has an excellent performance, much better than a simple MMSE filter for ISI compensation and clearly better than a decoder according to [3]. The difference between the decoders increases with growing block length as Fig. 5 shows compared to Fig. 4.

Fig. 6 presents a comparison of the performance of the MAP-DFE and a maximum likelihood sequence estimator (MLSE) for the considered space-time codes in a Rayleigh fading environment; 4-QAM is used and block length 6. The new decoder achieves almost the performance of the maximum likelihood decoder but with a much lower complexity even with the decoder threshold $P_{e,thres} = 0$.

Fig. 7 shows the interdependence between the achieved SER and a particular threshold for the decoder at $E_b / N_0 = 10$ dB; 4-QAM is used and the block length is 20 (as in Fig. 4). In addition it shows an information about the approximated complexity (considered are matrix inversions) in percent. For $P_{e,thres} = 0$ the complexity is 100%, and the simulated symbol error rate is SER = 2.5 e(-4). For $P_{e,thres}$ = 1e(-10) the same SER is found but with an approximated complexity of 46%.

V. Conclusions

The new decoder achieves almost the performance of the maximum likelihood decoder but with a lower complexity. The complexity – and consequently the available data flow rate - is scalable by varying the decoder threshold (Fig. 7). So, the decoder can be adapted to a given node complexity or a required quality of service. The presented inter-

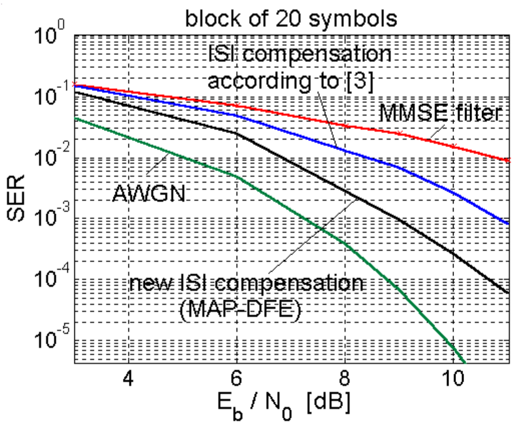

Fig. 4. SER performance comparison of different decoders (block length 20)

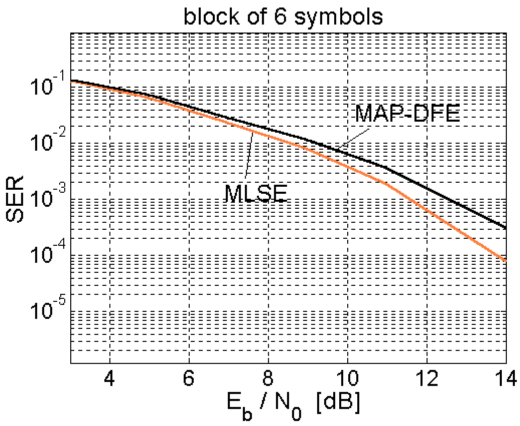

Fig. 6. Comparison of MLSE and MAP-DFE for block length 6

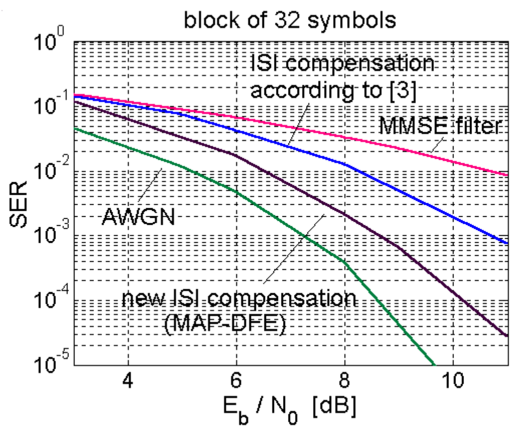

Fig. 5. SER performance comparison of different decoders (block length 32)

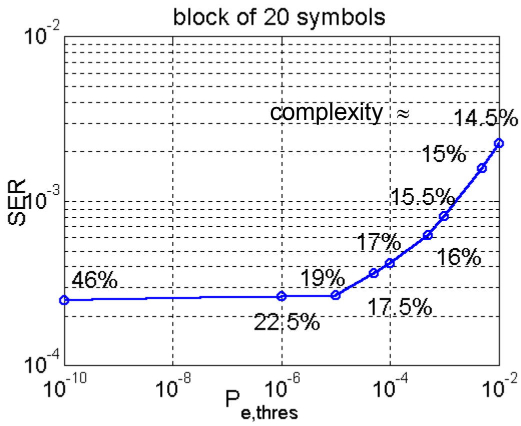

Fig. 7. SER versus decoder threshold for E_b / N_0 = 10 dB

ference compensation method can be used in a decoder for space-time codes but also for other applications, e. g. multi-user interference cancellation for CDMA-systems.

REFERENCES

[1] A. Wittneben, Marc Kuhn *"A new concatenated linear high rate space-time block code"*, VTC 2002 – Spring, in press.

[2] V. Tarokh, H. Jafarkhani, A. R. Calderbank, *"Space-time block codes from orthogonal Designs"*, IEEE Transactions on Information Theory (vol 45, pp. 1456-1467, July 1999).

[3] G. D. Golden, G. J. Foschini, R. A. Valenuela, P. W. Wolniansky, *"Detection algorithm and initial laboratory results using V- BLAST space-time communication architecture ",* Electronic Letters (vol. 17, Nov. 1998).

[4] G. J. Foschini, *"Layered space-time architecture for wireless communication in a fading environment when using multi-element antennas"*, Bell Labs Technical Journal, autumn 1996.

[5] A. Wittneben, *"A novel bandwidth efficient analog coding/decoding scheme for data transmission over fading channels",* Proceedings ICC 1994

[6] J. G. Proakis, *"Digital communications",* ISBN 0-07-113814-5, McGraw-Hill, Singapore, 1995.