Quasi-Orthogonal Space-Time Block Codes on Measured MIMO Channels

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Abstract

In this paper we study the performance of quasi-orthogonal space-time block codes (QSTBCs) on measured MIMO channels using four transmit and four receive antennas. We use QSTBCs with and without partial channel state information at the transmitter. At the receiver we compare a zero-forcing receiver and a maximum likelihood receiver. We demonstrate that applying our simple feedback scheme, the QSTBCs are robust against different MIMO channel realizations and they perform very well even in case of spatial channel correlations.

1. Introduction

The first space-time block code (STBC) for two transmit antennas has been proposed by Alamouti [1]. This scheme has transmission rate one and full diversity since two symbols are transmitted in two time slots according to a clever defined (2×2) code matrix. For more than two transmit antennas some codes are known achieving full diversity but lower rate, e.g. rate $3/4$ [2]. The basic technique to overcome the rate limitation of orthogonal STBCs for more than two transmit antennas is to allow a small amount of non-orthogonality in the STBC matrices. As a result, several full rate quasi-orthogonal STBC (QSTBC) schemes have been introduced [4], [3], [5].

Most of the STBCs are designed under the assumption that the transmitter has no knowledge about the channel. On the other hand, it has been shown that exploiting perfect channel state information (CSI) at the transmitter and at the receiver, outage performance is improved compared to the case when only the receiver has perfect channel knowledge. Low decoding complexity, high diversity and a higher code rate can be obtained even if only partial channel information is sent back to the transmitter [6]. In the scheme presented in [7] [8], with partial channel information at the transmitter, diversity is improved up to nearly the maximum value.

Research on adapting the block code at the transmitter to partial feedback has been an intensive area of research. However, mostly channel models with independent and identically distributed (i.i.d.) transfer coefficients have been used. While this is far from practical setups, the advantage of such a simplification is that much of the performance can be predicted in closed form mathematical expressions. Various measurements have shown that realistic MIMO channels provide a significantly lower channel capacity than idealized i.i.d. channels [9] due to spatially correlated antenna signals at the transmitter and at the receiver [10], [11].

In this paper, the performance of QSTBCs applied on measured channels or measurement based channel models is investigated. We utilize the so called Kronecker channel model [12], and QSTBC designed for four transmit and four receive antennas [2], [4]. As a transmission system we investigate a simple closed-loop transmission scheme first explained in [7], [8], that returns only one channel state information bit b per code block to the transmitter.

2. Quasi-OrthogonalSpace-Time Block Codes (QSTBCs)

QSTBCs [2], [4], [5] exist for $n_T = 2^k, k = 2, 3, 4, \cdots$ transmit antennas and for any number of receive antennas (n_R). In the following, we explain the impact of QSTBCs for four transmit antennas on an arbitrary number of receive antennas.

We start with the QSTBC for four transmit antennas and one receive antenna. Let us denote the baseband equivalent received signal $\hat{\mathbf{y}} = \mathbf{S}\mathbf{h} + \mathbf{n}$, where $\mathbf{S}$ is the QSTBC:

$$\mathbf{S} = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ s_2^* & -s_1^* & s_4^* & -s_3^* \\ s_3^* & s_4^* & -s_1^* & -s_2^* \\ s_4 & -s_3 & -s_2 & s_1 \end{bmatrix}, \tag{1}$$

$\mathbf{n}$ is the noise vector and $\mathbf{h} = [h_{11}, h_{12}, h_{13}, h_{14}]^T$ denotes the channel transfer vector. The received signal vector can be equivalently written as $\mathbf{y} = \mathbf{H}_v\mathbf{s} + \mathbf{n}$, where some conjugations in $\hat{\mathbf{y}} = [y_1, y_2, y_3, y_4]^T$ are used to define $\mathbf{y} = [y_1, y_2^*, y_3^*, y_4]^T$. $\mathbf{H}_v$ denotes an equivalent virtual (4×4) channel matrix, also containing conjugations of h_{ij}:

$$\mathbf{H}_v = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ -h_{12}^* & h_{11}^* & -h_{14} & h_{13} \\ -h_{13}^* & -h_{14}^* & h_{11}^* & h_{12}^* \\ h_{14} & -h_{13} & -h_{12} & h_{11} \end{bmatrix} \tag{2}$$

Applying matched filtering at the receiver by means of $\mathbf{H}_v^H$, we obtain a quasi-orthogonal Grammian matrix

$$\mathbf{G}=\mathbf{H}_v^H\mathbf{H}_v=\mathbf{H}_v\mathbf{H}_v^H=\mathrm{h}^2\begin{bmatrix}1 & 0 & 0 & X\\ 0 & 1 & -X & 0\\ 0 & -X & 1 & 0\\ X & 0 & 0 & 1\end{bmatrix}$$

with the channel gain h^2, defined as

$$h^2=|h_{11}|^2+|h_{12}|^2+|h_{13}|^2+|h_{14}|^2, \tag{3}$$

and a channel dependent interference parameter X, resulting in

$$X = 2\mathrm{Re}(h_{11}h_{14}^*-h_{12}h_{13}^*)/h^2. \tag{4}$$

The QSTBCs can be generalized for arbitrary values of n_R. Then the Grammian matrix has the same structure as above. In case of $n_R=4$ the channel gain h^2 and the channel dependent interference parameter X now result in:

$$\begin{aligned} h^2 &= \sum_{i=1}^{n_R} h^2(i),\\ X &= \frac{1}{h^2}\sum_{i=1}^{n_R} h^2(i)X^{(i)}\end{aligned}$$

for $i=1,2,3,4$ with:

$$\begin{aligned} X^{(i)} &= 2\mathrm{Re}(h_{i1}h_{i4}^*-h_{i2}h_{i3}^*)/h^2(i)\\ h^2(i) &= |h_{i1}|^2+|h_{i2}|^2+|h_{i3}|^2+|h_{i4}|^2.\end{aligned}$$

3. Code Selection Strategy

A simple closed-loop transmission scheme with one feedback bit per code block returned from the receiver to the transmitter can be easily applied to QSTBCs [8], [7] (Figure 1). We assume that the receiver can estimate the channel

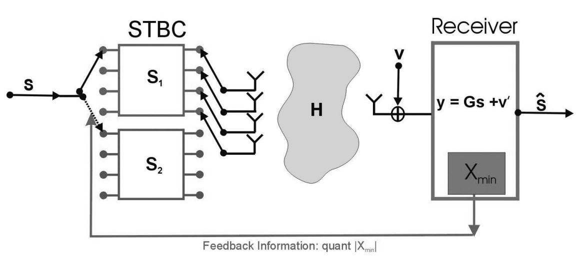

Fig. 1. Switching Strategy for $n_T=4, n_R=1$

and has perfect channel knowledge . On the receiver side we apply first matched filtering and then we use a ZF receiver or a ML receiver. On the transmit side we switch between two very similar QSTBCs, $\mathbf{S}_1$ given in (1) and $\mathbf{S}_2$:

$$\mathbf{S}_2=\begin{bmatrix}-s_1 & s_2 & s_3 & s_4\\ -s_2^* & -s_1^* & s_4^* & -s_3^*\\ -s_3^* & s_4^* & -s_1^* & -s_2^*\\ -s_4 & -s_3 & -s_2 & s_1\end{bmatrix}. \tag{5}$$

The corresponding virtual channel matrices are $\mathbf{H}_{v1}$ already defined in (2), if S_1 is used and $\mathbf{H}_{v2}$, if S_2 is used:

$$\mathbf{H}_{v2}=\begin{bmatrix}-h_{11} & h_{12} & h_{13} & h_{14}\\ -h_{12}^* & -h_{11}^* & -h_{14} & h_{13}\\ -h_{13}^* & -h_{14}^* & -h_{11}^* & h_{12}^*\\ h_{14} & -h_{13} & -h_{12} & -h_{11}\end{bmatrix}. \tag{6}$$

The two corresponding channel dependent interference parameters $X^{(i)}$ result in

$$X_1^{(i)} = \frac{2\mathrm{Re}(h_{i1}h_{i4}^*-h_{i2}h_{i3}^*)}{h^2(i)}, \text{if } \mathbf{S}=\mathbf{S}_1, \tag{7}$$

and

$$X_2^{(i)} = \frac{2\mathrm{Re}(-h_{i1}h_{i4}^*-h_{i2}h_{i3}^*)}{h^2(i)}, \text{if } \mathbf{S}=\mathbf{S}_2. \tag{8}$$

The resulting matrix $\mathbf{G}$ and the channel gain h^2 have the same structure as in the (4) and (3).

It is well known that $\mathbf{G}$ should approximate a scaled identity-matrix as far as possible to get full diversity and optimum Bit Error Ratio (BER) performance. This means, that the interference parameter X should be as small as possible. Therefore, the strategy is to transmit that code $\mathbf{S}_j,(j=1,2)$ that minimizes $|X|$. Since it is assumed that the receiver has full information about the channel, knowing h_{i1} to h_{i4}, the receiver can compute X_1 and X_2. With this information the receiver returns the feedback bit b informing the transmitter to select that code block $\mathbf{S}_j,(j=1,2)$ that leads to the smaller value of $|X|$. Obviously the control information sent back to the transmitter only needs one feedback information bit per code block.

4. Models of Correlated MIMO Channels

The Kronecker model [12] is a popular channel model often used in simulation of MIMO systems. The MIMO channel is modelled by

$$\mathbf{H}=\frac{1}{\sqrt{\mathrm{tr}(\mathbf{R}_T)}}\mathbf{R}_R^{\frac{1}{2}}\mathbf{V}\mathbf{R}_T^{\frac{1}{2}} \tag{9}$$

where $\mathbf{R}_R=\mathrm{E}\{\mathbf{H}\mathbf{H}^H\}$ is the $n_R\times n_R$ receive correlation matrix, $\mathbf{R}_T=\mathrm{E}\{\mathbf{H}^H\mathbf{H}\}$ is the $n_T\times n_T$ transmit correlation matrix, and $\mathbf{V}$ is a random $n_R\times n_T$ matrix with independent, Gaussian distributed complex-valued random elements with zero mean and unit variance. Both, $\mathbf{R}_R$ and $\mathbf{R}_T$ are estimated from the measurements. The normalization coefficient

$$\mathrm{tr}(\mathbf{R}_T)=\mathrm{tr}(\mathbf{R}_R)=\mathrm{E}\left\{\sum_{i=1}^{n_R}\sum_{j=1}^{n_T}|h_{ij}|^2\right\} \tag{10}$$

can be interpreted as the channel's total power transmission gain factor.

5. Measurement Setup and Simulation Results

5.1. Measurement Scenario

The channel measurements have been performed at the Institute of Communications and Radio-Frequency Engineering, Vienna University of Technology. A detailed description of the measurements can be found in [13]. The measurements have been performed with the RUSK ATM wideband vector channel sounder [14] with a measurement bandwidth of 120MHz at a centre frequency of 5.2GHz. At the transmit (TX) side, a virtual 20×10 matrix formed by a horizontally omnidirectional TX antenna and at the receive (RX) side an 8-element uniform linear array (ULA) of printed dipoles with 0.4λ inter-element spacing and 120° 3dB beamwidth have been used.

We have measured 193 frequency samples of the channel transfer function within the measurement bandwidth of 120 MHz. Using a virtual 4-element TX array, we created 130 different realizations of the MIMO channel matrix by moving this virtual array over all possible positions of the transmit array. In total we obtained $193 \times 130 = 25,090$ realizations of an (4×4) MIMO channel matrix.

5.2. Simulation Results

In Fig. 2-5 we show the simulation results corresponding to two different scenarios. The measurement environment for each scenario is explained in detail in [13]. For our simulations we have chosen two exemplary scenarios. Scenario A, denoted as Rx5D1 in [13], is characterized by a Non Line-of-Sight (NLOS) connection between transmit and receive antennas and scenario B (Rx17D1) has been chosen because it contains a LOS component, in contrast to scenario A. In both cases a big difference in ergodic channel capacity between the measured channel and the corresponding channel simulations using the Kronecker model is observed.

In our simulations, we have used a QPSK signal constellation. At the receiver side, a zero forcing (ZF) receiver as well as a maximum likelihood (ML) receiver has been used. We calculated the BER as a function of E_b/N_0 from our simulations, utilizing four transmit and four receiver antennas. We used all realizations of (4×4) MIMO channel matrices to simulate the performance of the measured channels and to estimate the correlation matrices for the Kronecker model. The resulting BER curves are compared with results obtained from simulations on an i.i.d. channel model.

Fig. 2 present the simulation results for scenario A where no LOS component exists and ZF receiver is applied. Fig. 3 shows the simulation results for the ML receiver. The difference between the results for the i.i.d. channel and the results obtained for the measured channel is small for both receivers. With code selection we substantially improve the BER performance of the measured channel, especially if the ZF receiver is applied, where the gain is 2.5 dB.
The Kronecker model leads to a big gap in BER performance compared with the i.i.d channels. If the ZF receiver is applied, with code selection we achieve the same BER performance of the Kronecker model as in a case of the measured channels without code selection. Applying the ML receiver, the code selection does not improve the BER performance substantially.

The special case, when there is a LOS component between transmitter and receiver, is illustrated in Fig. 4 for the ZF receiver. Fig. 5 shows the results for same scenario and the ML receiver. For both receiver types, there is a big difference in the BER performance between the i.i.d.chanel and the measured channel and the Kronecker model. The BER curve for the measured channel and the Kronecker model agree completely. Even, with code selection at the transmitter the difference between the i.i.d. channel, the measured channel and the Kronecker model remains quite remarkable.

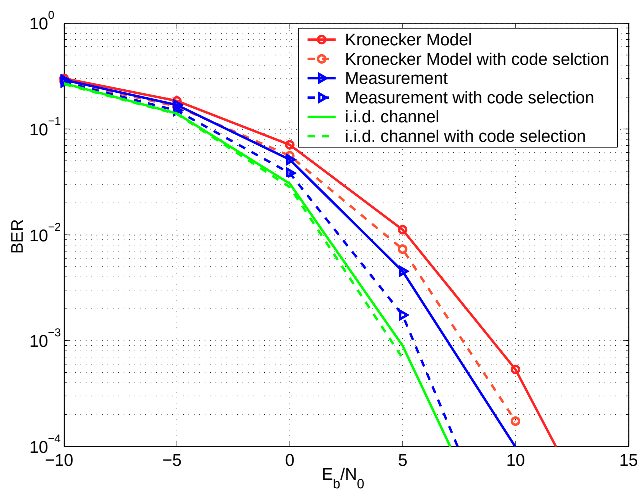

Fig. 2. Scenario A (NLOS) and ZF receiver

6. Conclusion

In this work we have analyzed the impact of weak and strong correlation on the performance of quasi-orthogonal space time block codes. Our simulations are based on two different measured indoor channels. We have shown that QSTBCs with simple feedback are robust against channel variations and they perform very well even on high correlated channels. We have shown that the Kronecker model sometimes overestimates the BER compared to the underlying measured channel.

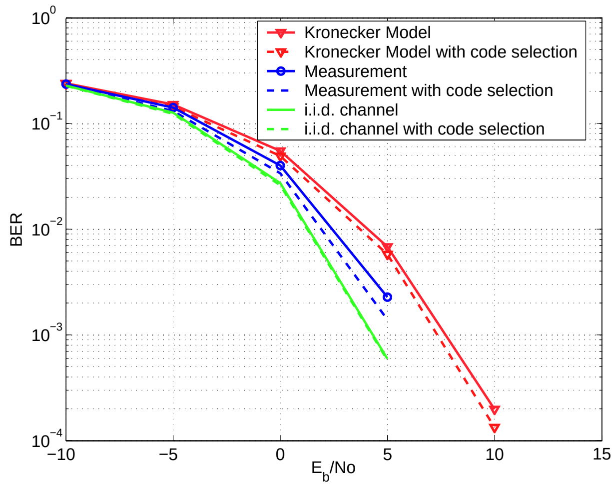

Fig. 3. Scenario A (NLOS) and ML receiver

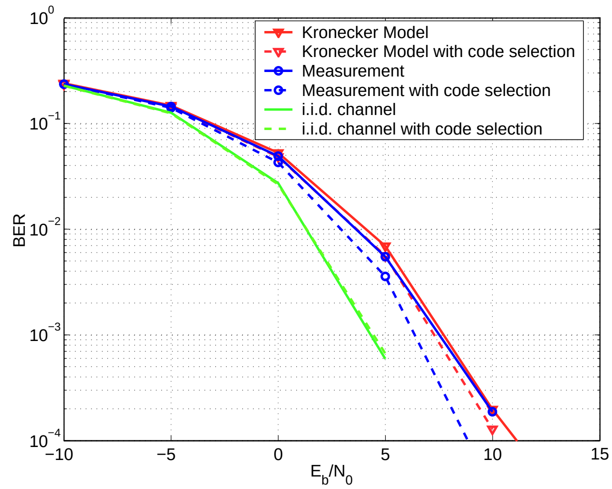

Fig. 5. Scenario B (LOS) and ML receiver

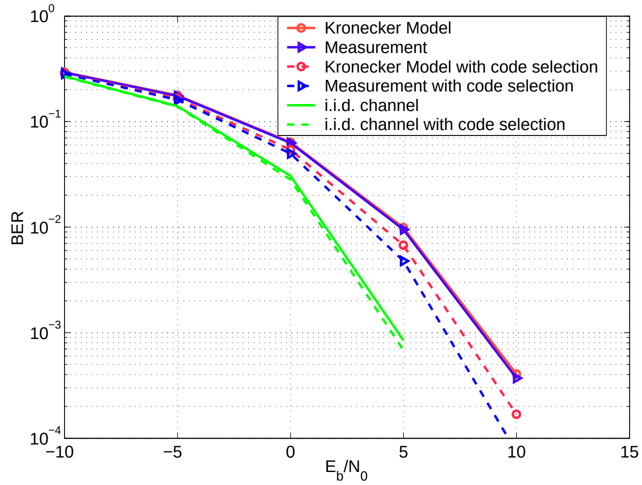

Fig. 4. Scenario B (LOS) and ZF receiver

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