Performance of Various Data Transmission Methods on Measured MIMO Channels

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***Abstract*— In this paper we discuss the performance of several data transmission schemes over measured MIMO-channels using four transmit antennas. We analyze uncoded and prefiltered data transmission with schemes using simple Extended Alamouti Codes with and without partial feedback. Our simulations are based on channel measurements and measurement based channel models. It is shown that the Extended Alamouti scheme using partial feedback is extremely robust against channel correlation and thus outperforms other transmission schemes.**

I. Introduction

In the analysis of space-time codes, it is usually assumed that the channel is perfectly known at the receiver. On the other hand, the channel knowledge at the transmitter is limited to channel statistics and the actual realization is unknown. It has been observed that significant performance gains can be achieved, even if only partial instantaneous channel information is available at the transmitter [1].

Research on adapting the block code at the transmitter to partial feedback has been an intensive area. 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 [2]. This is due to spatially correlated antenna signals at the transmitter and at the receiver [3], [4], [5].

In this paper, the performance of Space-Time Block Codes (STBCs) is investigated when applied to measured channels or measurement based channel models. Since for general MIMO transmission closed form expressions are available only for limited cases [6], our work concentrates on simulations. In particular, we utilize the so called Kronecker channel model [7], [8], and Extended Alamouti Space-Time Block Codes (EASTBC) [9], [10], designed for four transmit antennas. We investigate three different transmission systems, transmission without channel knowledge, TX prefiltering as proposed by M. Kiessling at. al [11] and a simple feedback scheme explained in detail in [12], [13], that returns only one channel state information bit b per code block to the transmitter. Depending on the value of b the transmitter switches between two predefined STBCs and chooses that code matrix which achieves higher diversity and approximate orthogonality of STBCs.

The paper is organized as follows. In Section II we give an overview over the EASTBC for four transmit antennas and an arbitrary number of receive antennas. Here, we explain the simple feedback scheme when only one control bit per code block is sent back to the transmitter. The system model and the transmission scheme is presented in Section III. In Section IV we give a brief overview over the well-known Kronecker channel model. In Section V the measurement setup and simulation results are discussed and in Section VI we draw some conclusions.

II. Extended Alamouti (EA) Scheme

The Extended Alamouti code [9], [10], [14] exists 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 Alamouti scheme for four transmit antennas and an arbitrary number of receive antennas.

1. EA Scheme for $n_T = 4, n_R = 1$

First, the special case of the (EASTBC) for four transmit antennas and one receive antenna is explained. Let us denote the baseband equivalent received signal $\hat{\mathbf{y}} = \mathbf{S}\mathbf{h} + \mathbf{n}$, where $\mathbf{S}$ is an EASTBC:

$$\mathbf{S} = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ s_2^* & -s_1^* & s_4^* & -s_3^* \\ s_3^* & s_4^* & -s_1^* & -s_2^* \\ s_4 & -s_3 & -s_2 & s_1 \end{bmatrix}. \quad (1)$$

The information symbols s_1 to s_4 are taken from a QPSK signal constellation. Furthermore, $\mathbf{n}$ is 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 channel matrix, also containing corresponding conjugations:

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

The virtual channel matrix is no more orthogonal as in a case of simple (2×1) Alamouti scheme [15]. Instead, we obtain a quasi-orthogonal Grammian matrix

$$\mathbf{G} = \mathbf{H}_v^H \mathbf{H}_v = \mathbf{H}_v \mathbf{H}_v^H = \mathrm{h}^2 \begin{bmatrix} \mathbf{I}_2 & X\mathbf{J}_2 \\ -X\mathbf{J}_2 & \mathbf{I}_2 \end{bmatrix}$$

with

$$\mathbf{I}_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \mathbf{J}_2 = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}, \quad (3)$$

the channel gain h^2, defined as

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

and a channel dependent interference parameter X, resulting in

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

2. EA Scheme for other values of n_R

The EASTBC can be generalized for arbitrary values of n_R. The resulting 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:

$$h^2 = \sum_{i=1}^{n_R} h^2(i), \quad (5)$$

$$X = \frac{1}{h^2} \sum_{i=1}^{n_R} h^2(i) X^{(i)} \quad (6)$$

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

$$X^{(i)} = 2\mathrm{Re}(h_{i1}h_{i4}^* - h_{i2}h_{i3}^*)/h^2(i) \quad (7)$$

$$h^2(i) = |h_{i1}|^2 + |h_{i2}|^2 + |h_{i3}|^2 + |h_{i4}|^2. \quad (8)$$

3. CSI Feedback Method

A simple feedback scheme with one feedback bit per code block returned from the receiver to the transmitter can be easily applied to the EA scheme [13]. In [13], two STBCs have been defined as:

$$\mathbf{S}_1 = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ s_2^* & -s_1^* & s_4^* & -s_3^* \\ s_3^* & s_4^* & -s_1^* & -s_2^* \\ s_4 & -s_3 & -s_2 & s_1 \end{bmatrix} \quad (9)$$

$$\mathbf{S}_2 = \begin{bmatrix} -s_1 & s_2 & s_3 & s_4 \\ -s_2^* & -s_1^* & s_4^* & -s_3^* \\ -s_3^* & s_4^* & -s_1^* & -s_2^* \\ -s_4 & -s_3 & -s_2 & s_1 \end{bmatrix}. \quad (10)$$

The corresponding virtual channel matrices result in:

$$\mathbf{H}_{v1} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ -h_{12}^* & h_{11}^* & -h_{14} & h_{13} \\ -h_{13}^* & -h_{14}^* & h_{11}^* & h_{12}^* \\ h_{14} & -h_{13} & -h_{12} & h_{11} \end{bmatrix}, \quad (11)$$

if $\mathbf{S}_\mathrm{j} = \mathbf{S}_1$, and

$$\mathbf{H}_{v2} = \begin{bmatrix} -h_{11} & h_{12} & h_{13} & h_{14} \\ -h_{12}^* & -h_{11}^* & -h_{14} & h_{13} \\ -h_{13}^* & -h_{14}^* & -h_{11}^* & h_{12}^* \\ h_{14} & -h_{13} & -h_{12} & -h_{11} \end{bmatrix}, \quad (12)$$

if $\mathbf{S}_\mathrm{j} = \mathbf{S}_2$.

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

$$X_1^{(i)} = \frac{2\mathrm{Re}(h_{i1}h_{i4}^* - h_{i2}h_{i3}^*)}{h^2(i)}, \text{if } \mathbf{S}_\mathrm{j} = \mathbf{S}_1, \quad (13)$$

and

$$X_2^{(i)} = \frac{2\mathrm{Re}(-h_{i1}h_{i4}^* - h_{i2}h_{i3}^*)}{h^2(i)}, \text{if } \mathbf{S}_\mathrm{j} = \mathbf{S}_2. \quad (14)$$

The resulting matrix $\mathbf{G}$ and the channel gain h^2 have the same structure as in a Eqn.(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. As $\mathbf{G}$ indicates, our scheme inherently supports full diversity $d = 4$ if $X = 0$. Therefore, the strategy is to transmit that code $\mathbf{S}_1$ or $\mathbf{S}_2$ 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 $\mathbf{S}_j (j = 1, 2)$ which leads to the smaller value of $|X|$. With this information the transmitter switches between $\mathbf{S}_1$ and $\mathbf{S}_2$ such that the resulting $|X|$ will correspond to $\min(|X_1|, |X_2|)$. Obviously the control information sent back to the transmitter only needs one feedback information bit per code block.

III. System Model and Transmission Schemes

In the following, we investigate the BER performance of several data transmission methods over measured (4×4) MIMO channels. For the evaluation of the channel models we simulated uncoded blind transmission (no channel knowledge at the transmitter), a TX prefiltering method proposed by Mario Kiessling et. al in [11] that relies only on the long-term statistics of the MIMO channel, and EASTBC coded transmission with and without partial instantaneous channel knowledge at the transmitter.

For uncoded transmission, the system can be modelled by

$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{n}, \quad (15)$$

where $\mathbf{s}$ is the transmit-signal vector with correlation $\mathbf{R}_\mathrm{s} = \mathrm{E}\{\mathbf{s}\mathbf{s}^H\} = \mathbf{I}_{n_T}$, i.e. assuming unity symbol power, $\mathbf{H}$ is the MIMO channel matrix, $\mathbf{y}$ is the receive vector and $\mathbf{n}$

is the additive noise vector at the transmitter which is also assumed to be uncorrelated, hence $\mathbf{R}_{\mathrm{n}} = \mathrm{E}\{\mathbf{n}\mathbf{n}^H\} = \sigma_n^2 \cdot \mathbf{I}_{\mathrm{n_R}}$.

In case of correlated channels non trivial TX prefiltering [11] can be applied and the system model can be described as

$$\mathbf{y} = \mathbf{H}\mathbf{U}_{\mathrm{t}}\mathbf{\Phi}\mathbf{D}\mathbf{s} + \mathbf{n} \tag{16}$$

where $\mathbf{\Phi}$ is a diagonal gain matrix with the power constraint

$$\mathrm{trace}\{\mathbf{\Phi}\mathbf{\Phi}^H\} = P_t. \tag{17}$$

The matrix $\mathbf{U}_{\mathrm{t}}$ consists of the transmit eigenvectors and $\mathbf{D}$ is a DFT matrix that spreads the data streams over all utilized eigenvectors to give equal BER at each subchannel. This leads to the minimum overall BER performance of this transmission type. An approximate solution for the optimum diagonal amplitude matrix $\mathbf{\Phi}$ has been presented by M. Kiessling as

$$\mathbf{\Phi} = \left(\mu^{-1/2}\mathbf{\Lambda}_{\mathrm{t}}^{-1/2}\sigma_n - \mathbf{\Lambda}_{\mathrm{t}}^{-1}\sigma_n^2\right)_+^{1/2} \quad , \tag{18}$$

where the constant μ is chosen as

$$\mu^{1/2} = \frac{\mathrm{tr}\left(\mathbf{\Lambda}_{\mathrm{t}}^{-1/2}\sigma_n\right)}{\mathrm{tr}\left(\mathbf{\Lambda}_{\mathrm{t}}^{-1}\sigma_n^2\right) + P_t} \tag{19}$$

to fulfill the power constraint. Here, $\mathbf{\Lambda}_t$ is the diagonal eigenvalue-matrix of the transmit correlation matrix. Note that one has to assure that all values $\Phi_{ii} > 0$, indicated by the plus subscript in (18). This means that in some cases the number of utilized eigenvectors has to be reduced such that the signal power assigned to each eigenmode is positive.

In the case of coded transmission we consider the transmission model described in Section II with and without one control bit sent back from the receiver to the transmitter. In this case we have:

$$\mathbf{y}_i = \mathbf{H}_{vi}\mathbf{s} + \mathbf{n}, \text{ with } i = 1, 2. \tag{20}$$

IV. Models of Correlated MIMO Channels

The Kronecker model is a popular channel model often used for simulation of MIMO systems. The MIMO channel is modelled by

$$\mathbf{H} = \frac{1}{\sqrt{\mathrm{tr}(\mathbf{R}_T)}}\mathbf{R}_R^{\frac{1}{2}}\mathbf{V}\mathbf{R}_T^{\frac{1}{2}} \tag{21}$$

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

$$\mathrm{tr}(\mathbf{R}_T) = \mathrm{tr}(\mathbf{R}_R) = \mathrm{E}\left\{\sum_{i=1}^{n_R}\sum_{j=1}^{n_T}|h_{ij}|^2\right\} \tag{22}$$

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

V. Measurement Setup and Simulation Results

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 [18]. The measurements have been performed with the RUSK ATM wideband vector channel sounder [16] 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 has been used, 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.

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.

2. Simulation Results

In Fig. 1-6 we show the simulation results corresponding to two different scenarios. The measurement environments for each scenario is explained in detail in [18]. For our simulations we have chosen two exemplary scenarios. Scenario A (Rx5D1) is characterized by Non Line-of-Sight (NLOS) connection between transmit and receive antennas. Scenario A shows a big difference in ergodic channel capacity between the real channel and the corresponding channel simulations using the Kronecker model. Scenario B (Rx17D1) has been chosen because it contains a LOS component, in contrast to scenario A and B. In this case there is a significant difference in ergodic capacity between real channel and the corresponding Kronecker model.

In our simulations, we have used a QPSK signal constellation. At the receiver side, a zero forcing (ZF) receiver has been used. We calculated the Bit Error Ratio (BER) as a function of E_b/N_0 from our simulations, utilizing four transmit and four receiver antennas. We used all realisations 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 uncorrelated i.i.d. channel model.

Fig. 1-3 present the simulation results for scenario A where no LOS component exists. For uncoded blind transmission (Fig. 1), there is a big gap between the BER curves of the i.i.d. channel, the measured channel and the Kronecker model. Using Tx-prefiltering (Fig. 2), we do not achieve a significant improvement of the BER performance. In coded transmission (Fig. 3), the difference between the results for the i.i.d. channel and the results obtained for the measured channel is much smaller. Using partial feedback the BER

performance of the measured channel and of the Kronecker model is very similar to the BER performance for the i.i.d. channel.

The special case when there is a LOS component between transmitter and receiver is illustrated in Fig. 4-6. Utilizing Tx-prefiltering (Fig. 5) or coding (Fig. 6), we only achieve a small improvement of BER results compared to uncoded blind transmission (Fig. 4). Even, by sending one control bit back to the transmitter the difference between the i.i.d. channel, the measured channel and the Kronecker model remains quite remarkable.

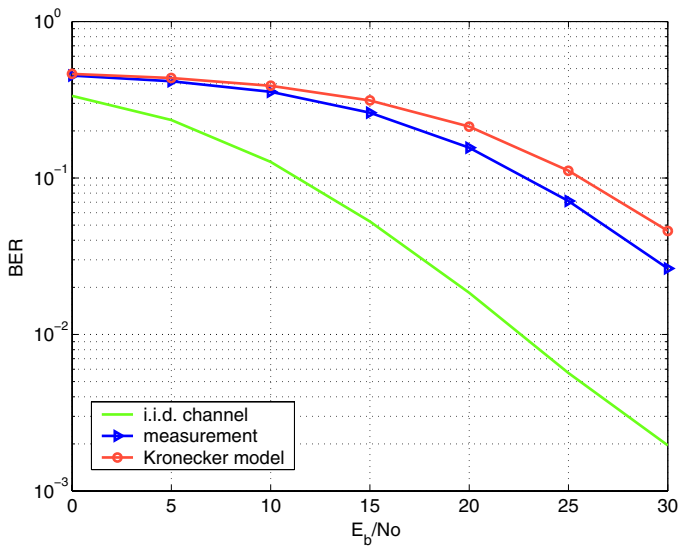

Fig. 1. Scenario A (NLOS), uncoded transmission

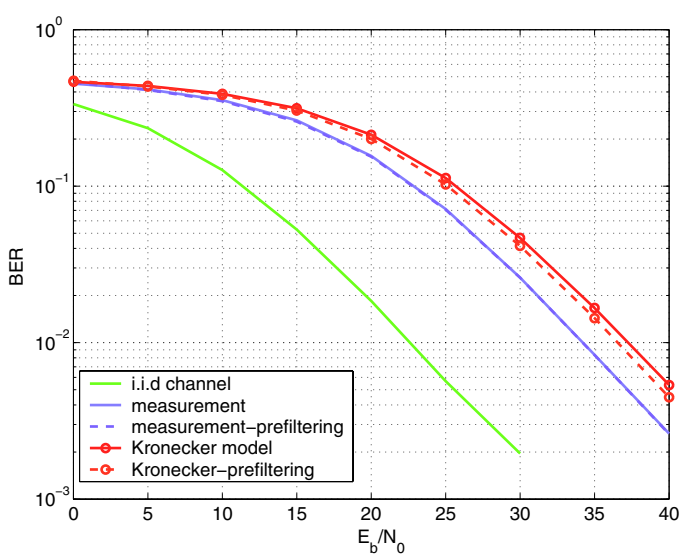

Fig. 2. Scenario A (NLOS), prefiltering

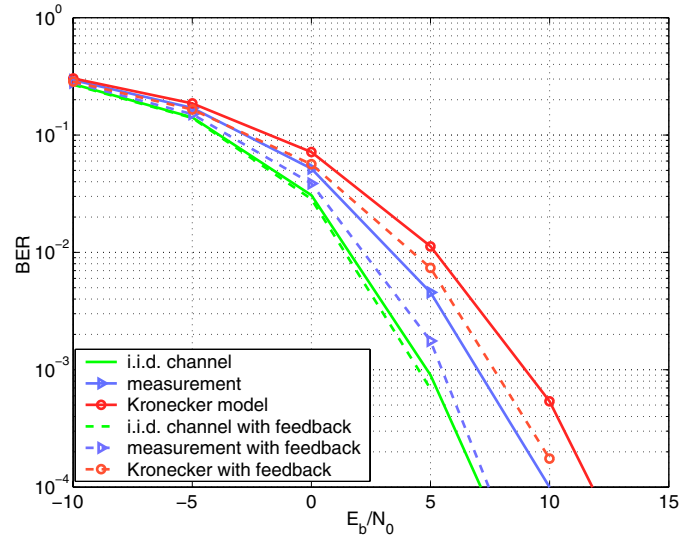

Fig. 3. Scenario A (NLOS), coded transmission

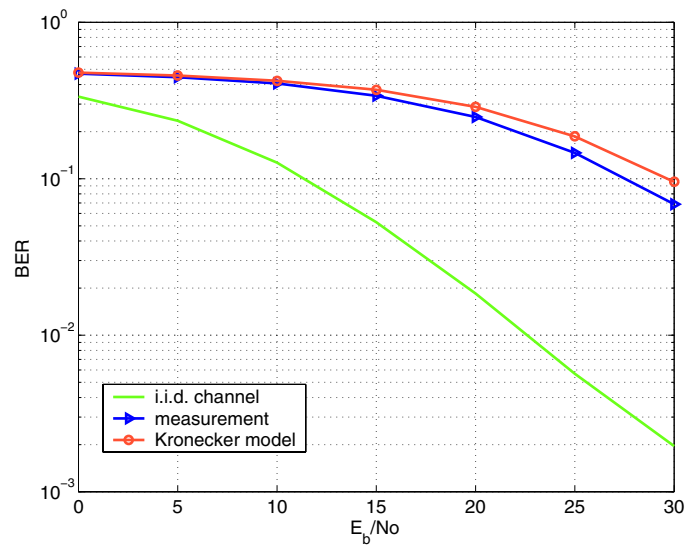

Fig. 4. Scenario B (NLOS), uncoded transmission

VI. Conclusion

In this work we have analyzed the impact of weak and strong correlation on the performance of different transmission schemes, namely uncoded blind transmission, Tx-prefiltering and EA coded transmission with and without a simple feedback scheme. Our simulations are based on two different, measured indoor channels. We have shown that coding with simple feedback is robust against substantially different channels and it performs very good with high correlation. Uncoded blind transmission and Tx-prefiltering show significant dependence on channel correlation but of course provides much larger spectral efficiency. Analyzing the BER performance we have shown that the Kronecker model sometimes overestimates the BER compared to the underlying measured channels types.

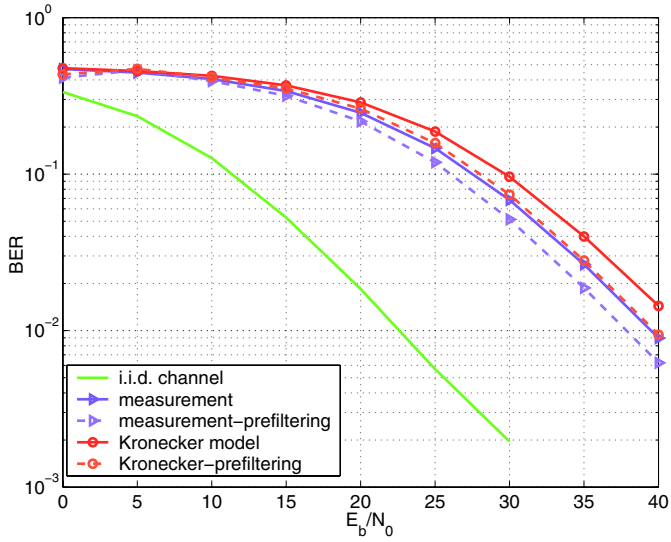

Fig. 5. Scenario B (NLOS), prefiltering

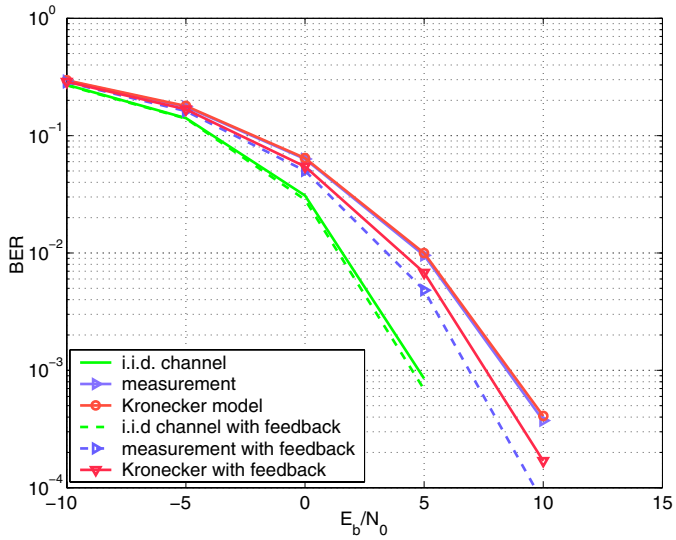

Fig. 6. Scenario B (NLOS), coded transmission

VII. Acknowledgment

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