Evaluation of Space-Time Coded MIMO Transmission in Measured Indoor Channels

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Abstract–**In this paper we evaluate the bit error ratio (BER) performance of the space-time coded multiple-input-multiple-output (MIMO) transmission using measured indoor radio channels. Based on a novel measurement-based antenna test bed, we compute channel matrices for three different MIMO antenna configurations designed for WLAN-type application. We focus on four main points, namely, the effect of the power imbalance between the channel coefficients, the effect of spatial correlation, the influence of antenna orientation and selection combining (SC) at the receiver. Because of nonuniform directions of arrival of realistic radio channels, directional non-overlapping antenna patterns cause power imbalances between MIMO channel coefficients resulting in BER degradation. For an array with directional overlapping patterns, the BER performance is even worse due to sensitivity to antenna orientation. The effect of spatial correlation on the BER is found to be small.**

I. Introduction

Multiple-input-multiple-output (MIMO) systems have recently emerged as one of the most significant technical breakthroughs in wireless communication [1]. The main idea of the MIMO systems is the *space-time* signal processing in which time is complemented with the spatial dimension by using multiple spatially distributed antennas. To improve the quality of the received signal in the MIMO systems, space-time block codes (STBCs) have been introduced [2], [3] as a technique that improves signal quality by utilizing the spatial diversity at the transmitter side.

Typically, channel models with independent and identically distributed (i.i.d.) transmission coefficients are used for evaluating the performance of MIMO systems. 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 due to spatially correlated signals [1], [4]. Considering indoor propagation for WLAN-type applications, in [5] and [6] performance of space-time codes on measurement channels have been studied.

In this paper we evaluate the bit error ratio (BER) of the coded MIMO transmission using realistic antenna configurations and measured indoor radio channels. The rate-one quasi-orthogonal space time block code (QSTBC) for four transmit antennas and an arbitrary number of receive antennas is utilized in simulations. The realistic antenna configuration used makes these measurements more attractive than those reported in [5] and [6]. We study the effect of the power imbalance between the channel coefficients and utilize a selection combining (SC) at the receiver to improve the system performance. Furthermore, we analyze the influence of antenna orientation and spatial correlation on the system performance.

II. MIMO Channel Measurements

II-A. Measurement scenario

Measurements were conducted in an indoor environment at 2.1 GHz carrier frequency. Two dual-polarized elements (four channels) separated by 4.2 wavelengths ($\approx$ 63 cm) were used at the transmitter (TX). The spherical antenna array with 32 dual-polarized antenna elements were used at the receiver (RX). The receiver and the transmitter heights were 1.5 and 5.2 meters, respectively. The measurement route began in a open hall and ended in a corridor (Fig. 1. (a)). The receiver moved at 0.4 m/s speed. More details about the measurement system and environment can be found in [7], where 'FS1' denotes the measurement route considered in this paper.

II-B. Laptop antennas

We consider three different receive antenna configurations [8]:

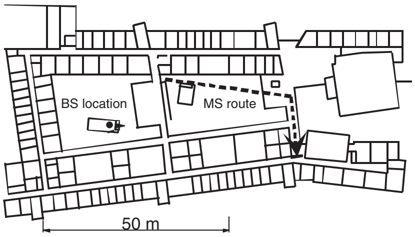

Fig. 1. Map of indoor environment.

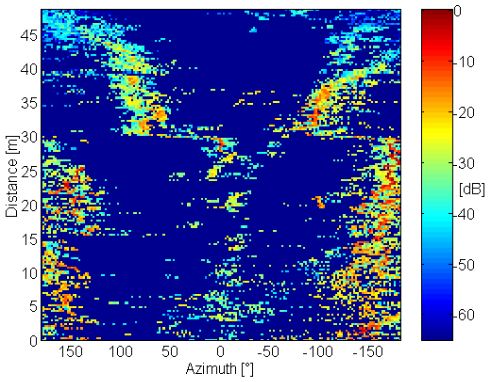

Fig. 2. Azimuth angles of arrival along the route.

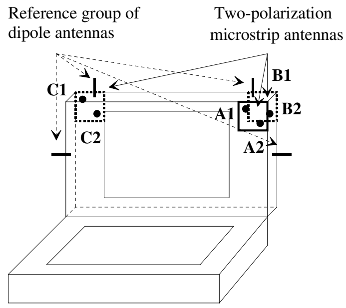

Fig. 3. Laptop antennas.

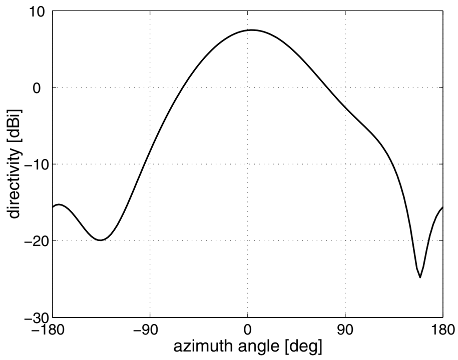

Fig. 4. Simulated directivity of the microstrip patch antenna, vertical polarization shown.

RX1 One dual-polarized patch antenna is located at both sides of the "laptop cover" (feeds A1, A2, B1, B2 in Fig. (3)).

RX2 Two dual-polarized patch antennas are located at the same side of the cover pointing away from the user (feeds B1, B2, C1, C2). Inter-element spacing of the antennas using RX2 is 2λ.

Dipole The dipole configuration consists of two vertical and two horizontal half-wavelength dipoles, as shown in Fig (3).

In Fig. 4 simulated directivity of the microstrip patch used in configurations RX1 and RX2 is shown. The dual-polarized microstrip patch element used in configurations RX1 and RX2 has been described in more detail in [8]. The field patterns of vertical and horizontal polarization unities (e.g. A1 and A2) are almost identical with a 90° antenna rotation due to symmetry. For each polarization unity the vertical and horizontal plane patterns are also similar. The cross-polarization discrimination between vertical and horizontal polarizations of each polarization unity is more than 12 dB in the forward side direction [8]. The use of two polarizations provides robustness against polarization mismatches, potentially arising in line-of-sight conditions with single-polarized receive antennas. The gain of the receive antenna is 7.8 dB. All antennas considered in this paper are assumed to have ideal radiation efficiency; in practice implementation losses may reduce the antenna gain.

II-C. Data processing

II-C.1. Measurement-Based Antenna Test Bed (MEBAT)

The direction-of-arrival, delay and polarization of the plane waves impinging on the spherical receive antenna array were estimated using the method presented in [9]. The post-processed data were combined with the dual-polarized 3D radiation patterns of the laptop antennas using the measurement-based antenna test bed (MEBAT) [10]. The channel matrices were computed for eight different azimuthal antenna orientations (45° grid) at each measurement instance. The output of MEBAT is a sequence of channel matrices (over the measurement route), that includes the effect of the non-isotropic field patterns of the laptop antennas.

II-C.2. Removal of large-scale fading

In this study we use wavelet-based regression for removing large-scale fading from the signal. The signal is binned into non-overlapping bins of width eight samples (2 wavelengths), and sample average is taken over each bin. From the resulting pre-smoothed signal the large-scale power trend is estimated with wavelet denoising using Donoho's threshold [11]. This wavelet-based regression method finds a smooth large-scale trend and is also able to abrupt changes in the non-stationary signal. A more detailed description of the detrending method is given in [12].

II-C.3. Normalization of channel matrices

Whereas trend removal "stationarizes" the signal power over time, power normalization is required to scale the average power in order to apply fair signal-to-noise ratio (SNR) in BER simulations. There are several ways to normalize the channel matrices, and different normalizations will lead to different results. We use the following notation. Indices i, j, n, and l refer to rows, columns, matrix indices (time snapshots), and antenna look directions, respectively ($n = 1, \ldots, N$, $l = 1, \ldots, L$). We denote the (i, j)th matrix element with h_{ij}. and $\text{ave}_x[\cdot]$ denotes sample mean over index x. In this paper we have $N = 1712$ and $L = 8$. Three normalization methods are employed due to the following rules:

M1 Remove large-scale signal power trends from the sequence of channel coefficients $\{|h^l_{ij,n}|\}^N_{n=1}$ and normalize each coefficient to unit mean power: $\text{ave}_n[|h^l_{ij,n}|^2] = 1$. Repeat this normalization for all i, j, l. The theoretical counterpart of this normalization is $E[|h_{ij}|^2] = 1$, i.e., each channel matrix element has unit average power over time.

M2 Remove large-scale power trends from the sequence of Frobenius norms $\{\|\mathbf{H}^l_n\|_F\}^N_{n=1}$ and normalize the matrix power to $n_r n_t$: $\text{ave}_n[\|\mathbf{H}^l_n\|^2_F] = n_r n_t$. Repeat for all l. This corresponds to the theoretical power normalization with $E[\|\mathbf{H}_n\|^2_F] = n_r n_t$. The difference to method M1 is that individual entries of $\mathbf{H}$ may have different average powers; this is called the channel coefficient power imbalance. With this overall power normalization, each antenna orientation, l, is normalized to the same power; hence in BER simulations antenna orientation has no effect.

M3 Remove large-scale trends (in dB) from the sequence of summed squared Frobenius norms $\{P_n\}^N_{n=1}$, where $P_n = \text{ave}_l[\|\mathbf{H}^l_n\|^2_F]$. Normalize the channel matrices so that $\text{ave}_n(P_n) = n_r n_t L$ ($L = 8$). After this normalization the average (over all antenna orientations) matrix power is the same as with method M2, but the power differences between different antenna orientations are preserved.

The first power normalization method eliminates power imbalances between channel coefficients. The second method leaves them unaffected but eliminates imbalances in average powers between different antenna look directions, whereas the third method leaves also these unaffected and removes a large-scale trend from the average power received over all directions. Comparing BER results between normalizations M1 and M2 will be used to illustrate the effect of channel coefficient power imbalance, whereas comparing BER results between M2 and M3 will reveal the effect of antenna orientation on the SNR. M3 is the most realistic normalization and will be used to predict BER performance under real-world conditions.

III. Space-Time Coded Transmission

Assuming $n_t = 4$ transmit antennas, $n_r = 1$ receive antenna and a rate- one QSTBC the received signal can be written as

$$\hat{\mathbf{y}} = \mathbf{S}\mathbf{h} + \mathbf{n}, \quad (1)$$

where $\mathbf{S}$ is the QSTBC from [3] with

$$\mathbf{S} = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 \\ -s_2^* & s_1^* & -s_4^* & s_3^* \\ -s_3^* & -s_4^* & s_1^* & s_2^* \\ s_4 & -s_3 & -s_2 & s_1 \end{bmatrix}, \quad (2)$$

$\mathbf{n}$ 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 in (1) can be equivalently written as

$$\mathbf{y} = \mathbf{H}_v \mathbf{s} + \mathbf{n}, \quad (3)$$

where some conjugations in $\hat{\mathbf{y}} = [y_1, y_2, y_3, y_4]^T$ are used to get $\mathbf{y} = [y_1, y_2^*, y_3^*, y_4]^T$. $\mathbf{H}_v$ denotes the equivalent virtual (4×4) channel matrix (EVCM). This matrix is a highly structured (4×4) array only consisting of the elements $h_{i,j}$ including some sign inversions and complex conjugates of $h_{i,j}$. The channel coefficients $h_{i,j}$ are extracted from the channel measurements.

Using quasi-orthogonal code design, pairs of transmitted symbols can be decoded independently and a small loss of diversity is due to some coupling terms between the estimated symbols. At low SNR the performance of the QSTBC is better than that of the orthogonal STBC (OSTBC), but it is worse at high SNR. This is due to the fact that the slope of the BER curve at higher SNR is determined by the diversity order [3] of the system. Since the BER performance at low-to-medium SNR values is of practical interest in concatenated coding systems where the STBC is used as an inner code, the chosen rate one QSTBC is an attractive candidate for practical implementations, especially due its simple ML decoding algorithm.

IV. Simulation Results

In our simulations we calculate the BER as a function of SNR using an ML receiver and a QPSK signal constellation. We consider (4×2) and (4×4) systems with QSTBCs and compare the results with QSTBCs for $(4 \times n_r), n_r = 2, 4$ operating on an i.i.d. channel. We focus on four important points, namely

- the effect of the power imbalance (Fig.(5)),
- the effect of spatial correlation,
- the effect of the selection combining (SC) (Fig.(6)),
- the effect of the antenna positions (Fig.(7)).

IV-A. Channel coefficient power imbalance

In Fig. (5) we compare data transmission with antenna configuration RX1 with channel coefficients normalized by method M1 with results obtained with power normalization M2 to illustrate the effect of the channel coefficient imbalance. In both cases, there is only a slight performance loss compared to results on the i.i.d. channel. By retaining the average power differences between channel matrix elements (normalization method M2), it can be seen that there is no degradation in the BER performance at low E_b/N_0 values (up to 0 dB). Compared to the i.i.d. channels there is a E_b/N_0 loss of about 1.5 dB at 10^{-3} BER. Compared to the M1 normalization, the degradation is about 1 dB at 10^{-3} BER.

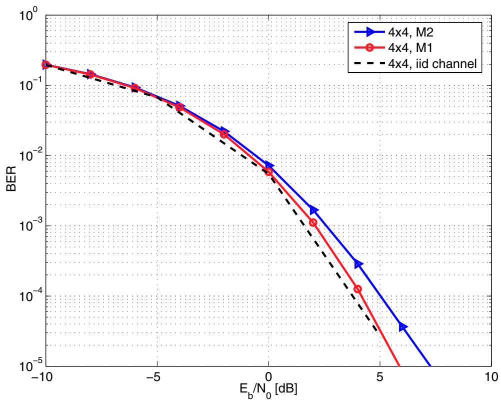

Fig. 5. Performance of QSTBC for $n_t = 4$ and $n_r = 4$ on indoor measured channels illustrating the effect of power imbalance with antenna configuration RX1.

IV-B. Spatial correlation

The spatial envelope correlation coefficients between entries of the (4×4) channel matrices were computed from channel matrices normalized by method M1. These correlation coefficients depend on the antenna orientation. The maximum values over all non-diagonal entries of the correlation matrix and over all orientations are only 0.32, 0.30, and 0.22 for RX1, RX2, and the dipole arrays, respectively. It turned out that the BER degradations due to these spatial correlations are negligible compared to the degradations caused by the power imbalances between MIMO channel gains. Interestingly enough, unlike for spatial correlation, no analytical investigations of the effect of channel gain imbalance on the system performance using space-time codes seem to be available in the literature.

IV-C. Receiver selection diversity

In the simulations presented in Fig. 6, two dual-polarized receive antennas were used in the (4×4) antenna system and in the (4×2) case two horizontally polarized receive branches pointing to opposite directions were selected. The channel normalization M3 was applied. Comparing to i.i.d channels, we can see a small degradation of the BER performance for the (4×2) system. For the (4×4) system with QSTBCs the performance gap of is about 3 dB at 10^{-3} BER when compared with the i.i.d. channels. We also tested a coded (4×2) system with selection combining (SC) so that two strongest receive branches (out of the total of four) were selected at each channel use. From Fig. 6 it can be seen that the performance of the coded (4×2) QSTBC is close to the full (4×4) system. Note that the (4×2) system with SC achieves the same diversity order as the full (4×4) system with smaller computational and implementation complexity. Due to the directional nature of the antennas and the specific channel characteristics shown in Fig. 2 some antennas receive most of the signal power, whereas others receive much less power. Hence the coded (4×2) system with receiver selection combining realizes almost the same performance gain as the (4×4) system.

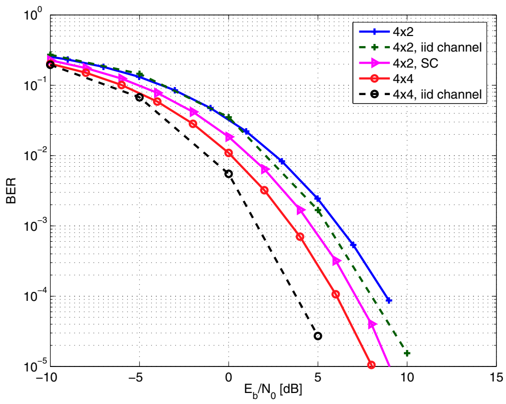

Fig. 6. Performance of QSTBC for $n_t = 4$ and $n_r = 2, 4$ on indoor measured channels compared to i.i.d channels, with and without selection combining (SC) (antenna configuration RX1, power normalization $M3$).

IV-D. Antenna configurations

In Fig. (7) we compare the BER results of antenna groups RX1 and RX2 with the dipole antennas, where the coded (4×4) MIMO transmission was simulated. The transmission in the case of RX2 with normalization $M3$ shows the worst performance, since in this case the receive antennas are pointing to the same direction. In case of RX1 the performance of the transmission is close to the performance of the dipole antennas, because the effect of the antenna patterns is not dominant like in the RX2 case as shown in [8]. This is confirmed by plotting the BER for RX2 with normalization M2, which removes the effect of power imbalance of different antenna orientations. In this case, RX2 performs approximately as well as RX1. However, the deleterious effect of bad antenna orientation is in the order of 5 dB at BER=10^{-3} for RX2, when compared with the i.i.d. channels. Summarizing our results, we can say that arrays with directional overlapping antenna patterns are very sensitive to antenna orientation, which results in a considerable degradation of the average BER performance.

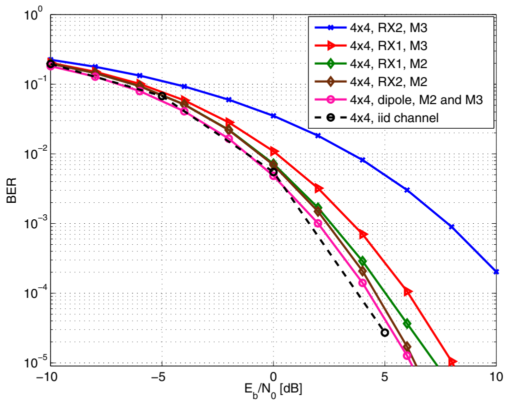

Fig. 7. Effect of different antenna configurations and power normalization methods on the performance of QSTBC for $n_t = 4$ and $n_r = 2, 4$ on indoor measured channels compared to i.i.d channels.

V. Summary of Results and Conclusion

We have evaluated the BER performance of space-time coded transmission using four transmit antennas and two and four receive antennas over measured indoor radio channels. We summarize our findings a follows:

- Real-world radio channels exhibit non-uniform directions-of-arrival. Because of this, antenna directivity and field pattern orientation play a key role in communication system performance.
- The main reasons for the BER degradation on the measured indoor channels, compared to the i.i.d. Rayleigh fading case, in increasing order of severity are: spatial envelope correlation, power imbalances between channel matrix coefficients, and antenna orientation.
- With suitable antennas, the BER performance, averaged over all antenna orientations, can be within 1-2 dB away from the performance on i.i.d. Rayleigh channels at a BER=10^{-3}.
- Spatial correlation plays a minor role, at least in the NLOS scenario examined in this paper.
- Using directional element patterns pointing in the same direction, as with the linear array, results in sensitivity on antenna orientation and several dBs of SNR degradation occurs compared to the i.i.d. Rayleigh case.
- Using directional element patterns pointing in different directions eliminates, to a certain extent, the effect of antenna orientation, but increases channel gain power imbalances. Using selection diversity at the receiver may result in a more economical RF implementation at the cost of a small BER degradation.
- A simple dipole array can have a good performance, because its elements are non-directional and cover a wide spatial angle. Therefore, this array is relatively insensitive to antenna orientation and does not induce large channel gain power imbalances.

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