2×2 MIMO at Variable Antenna Distances

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ABSTRACT

Various publications have drawn a precise picture on how correlation and capacity change when decreasing the receive-antenna distance of a 2×2 MIMO transmission to less than 0.1 λ; however, little is known on how today's commonly employed coding schemes actually perform under such harsh conditions.

In this paper, we evaluate—by measurements with a testbed—the uncoded BER over antenna distance performance of: spatial multiplexing, a linear dispersion code, the Golden Code, as well as Alamouti coding. We show, that even at very small antenna distances, a significant gain compared to an ordinary 1×2 SIMO transmission can be measured.

I. MOTIVATION

MIMO has emerged as a key technology in modern communication systems that pretend to achieve higher data rates and/or reliability. The idea behind MIMO is to exploit the presence of, in the optimum, independent multipath fading. In reality, however, correlation between the different propagation paths lowers the achievable link capacity. Small transmit antenna spacings, as demanded by today's ever smaller devices, are one major cause of such undesired interdependence.

To the authors' knowledge, the influence of antenna spacing on the BER over SNR performance of 2×2 space time coding schemes has neither been studied theoretically nor by measurements systematically. However, some results exist that relate antenna spacing, correlation, and capacity. This provides us with an expectation for the BER over SNR performance of the radio link at small antenna distances.

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II. EXISTING RESEARCH

Utilizing 2-D shooting and bouncing ray-tracing, [1] concludes for indoor scenarios a significant drop in capacity for spacings smaller 5 λ. Also in [2] and [3], a significant drop in capacity for spacings smaller than 4 λ is predicted by using a multipath cluster channel fading model. Leading to similar results, other theoretic papers like e.g. [4] and [5] also ignore the fact that small inter-element antenna spacing will cause mutual coupling. The same is true for multiplexed channel sounding of MIMO channels using a single transmit and receive antenna. Used for example in [6] and [7], this simplification—often referred to as "virtual antenna arrays"—also neglects the interaction between the two transmit antennas. In [8], the angle of arrival is obtained by true 4×4 MIMO channel sounding, which is then used to calculate the power angle spectrum, and next the spatial correlation as a function of antenna spacing.

Using a geometrically based statistical channel model, special emphasis on mutual coupling is put in [9]. A curve of capacity versus antenna distance with and without mutual coupling is derived. Full capacity is reached at about 0.3 λ and larger. Reference [10] accounts for mutual coupling effects by full-wave electromagnetic antenna simulations and leads to the same results. These results are explained by the fact that coupling changes the antenna patterns *individually* as the antennas are moved closely to each other. Therefore, a decorrelating effect is observed. Also [11] takes mutual coupling into account to theoretically show that capacity is decreased substantially if the spacing gets smaller than 0.5 λ.

There also exist channel sounding experiments where four antennas have been actually placed (not just virtually) in distances down to 0.2 λ [12–14]. The papers conclude that capacity is near i.i.d. till 0.2 λ. They also explain this by mutual coupling effects. In [15], the same results are achieved by a completely different approach; namely, MIMO systems were measured and characterized in a so-called reverberation chamber that represents the isotropic

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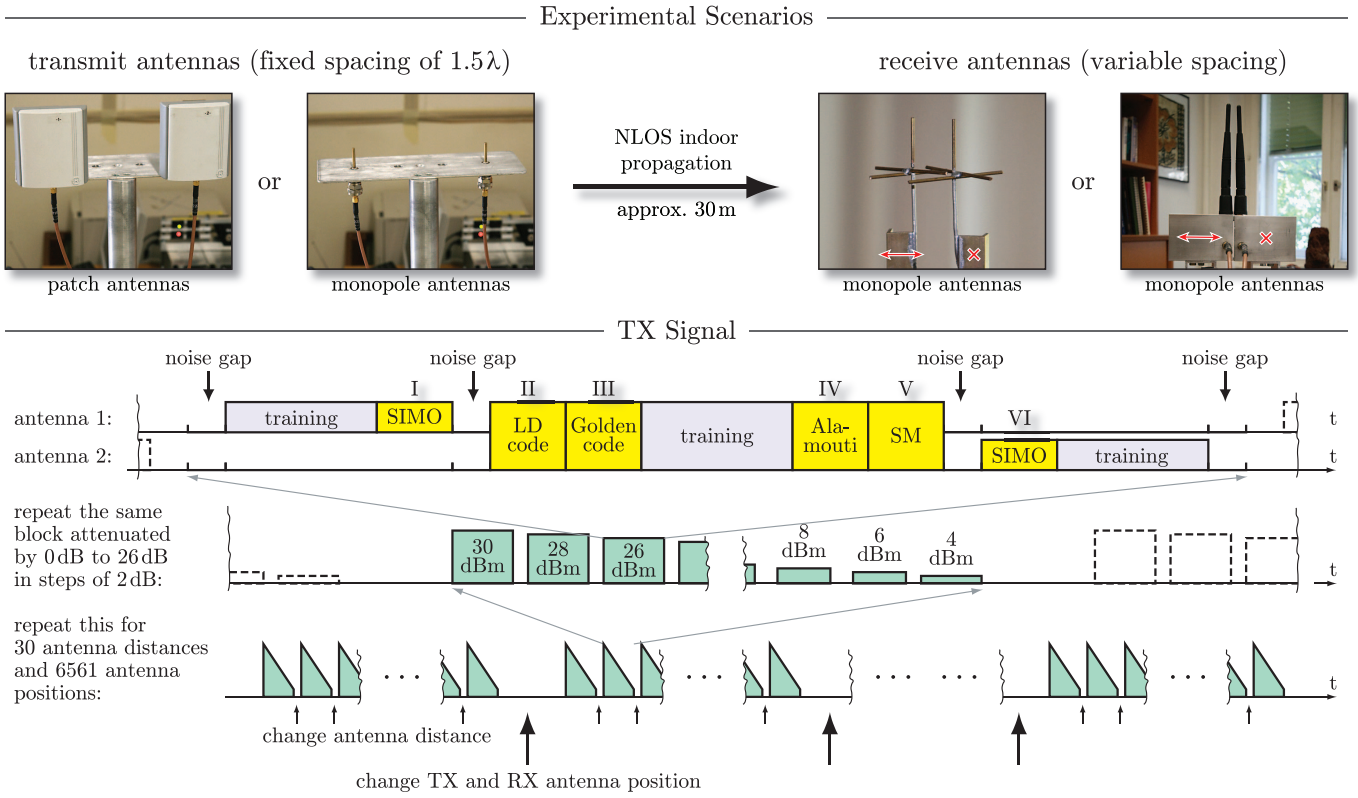

Figure 1. Antennas and transmit signal used.

multipath environment. Compact antenna designs are presented in e.g. [16]. Summarizing, taking mutual coupling into account, spacings of 0.2 to 0.5 λ should be sufficient to reach nearly full capacity. But does this hold true for a "real" 2×2 transmission and which code does actually perform best?

III. THE EXPERIMENT

To investigate the BER over SNR performance of a 2×2 radio-link, we utilized our "Vienna MIMO Testbed" [17, 18]. At a data rate of 400 kbits/s, we transmited QAM modulated and RRC filtered data blocks from either one or two transmit antennas to two receive antennas (see top of Figure 1). After storing the received baseband data samples on hard-disk drives, signal processing was carried out off-line in MATLAB with floating point precision.

III-A. Transmitting Data & Training

The yellow blocks in Figure 1 indicate the six different data blocks transmitted (numbered from I to VI). To make the comparison fair

- each block incorporates exactly 64 bits of data,
- lasts for exactly 160 µs (=400 kbit/s),
- and is transmitted at the same total power (sum of the power fed into both antennas).

The six blocks are coded the following

I: *SIMO 1:* 16 symbols, 16-QAM modulated, transmitted on antenna 1.

II: *Linear Dispersion code:* 32 symbols, linearly dispersed in space and time according to the number theory enhanced space time codes presented in [19]

III: *Golden Code:* 32 Golden coded symbols. The Golden Code is a 2×2 full-rate, full-diversity, space-time code with non-vanishing determinants [20, 21].

IV: *Alamouti:* 16 symbols, 16-QAM modulated and then Alamouti space-time coded [22].

V: *Spatial Multiplexing:* 32 symbols, where 16 symbols each are 4-QAM modulated to be transmitted independently on antenna 1 and antenna 2, respectively [23].

VI: *SIMO 2:* Same as SIMO 1 in item I, but the signal is transmitted on antenna 2 instead.

At the receiver, the incoming data samples were at first synchronized by the use of the training sequences (shown in gray in Figure 1). These 4-QAM modulated, 511 samples-long training sequences were afterwards also used to estimate the channel almost perfectly. In addition, the

position of the data blocks relative to the training was also constantly permutated during the experiment. Finally, maximum likelihood symbol detection is required at the receiver to achieve competitive performance. For the Alamouti code, this ML receiver can be implemented using a matched filter whereas for the LD Code and the Golden Code a sphere decoder is required. This sphere decoder has to search over a maximum number of 256 possible transmit symbol vectors since four 4-QAM symbols are encoded in one block.

The SNR at the receiver (it has to be the same for all data blocks) was estimated precisely by the use of "noise gaps" – i.e. spaces between the data blocks in Figure 1 during which nothing is transmitted so that only noise is still received.

III-B. Detecting Interference

When evaluating the BER over SNR performance of a system one has to make sure that the measurement is not disturbed by undesired third-party interference (e.g. microwave ovens, wireless LAN, Bluetooth). Since such interference is unavoidable, we detected it by the use of noise gaps (see the spaces between the data blocks in Figure 1). Finally, we discarded all destructed data blocks.

III-C. Averaging the Scenario

Each of the **six data blocks** is separately decoded at the receiver (using the same channel estimate and synchronization), leading to an estimated SNR and BER each.

We then repeat the whole transmission frame **14 times**, but attenuate the transmit signal by 0 dB, 2 dB, 4 dB,... 26 dB. This leads to a lower, by the attenuation factor decreased, SNR at the receiver (see also Figure 1).

Next, the resulting 6×14 blocks are transmitted at **30 different antenna spacings** (see also Figure 1). We mounted the left of the two transmit antennas on a stepper motor driven linear guide. The special shape of the ground-plane rods of the $\lambda/4$-monopole antennas allows for moving the antennas towards each other as closely as $0.02\,\lambda$ without touching.

The resulting $6\times14\times30$ blocks are transmitted at **9×9 different xy-positions of the transmit table**. This is achieved by a stepper motor controlled linear positioning unit moving the antenna arrangement. The area covered in the measurement is a $3\,\lambda\times3\,\lambda$ square. The positions were distributed uniformly in this area.

Finally, the resulting $6\times14\times30\times9^2$ blocks are transmitted at **9×9 different xy-positions of the receive table**. This is achieved by another stepper motor controlled linear positioning table similar to the transmit table. In addition, the receive antenna was also rotated between 0 and 360 degrees uniformly distributed.

All $6\times14\times30\times9^2\times9^2 \approx 17$ million blocks are subject to averaging over all $9^2\times9^2$ transmit and receive table positions. This leads to an average BER for each average SNR, transmission scheme, and antenna distance.

III-D. Calculating the SNR Required for 1% BER

We finally interpolate the measured BER over SNR results to obtain the SNR required for a BER of 1 %, for transmission scheme, and antenna distance.

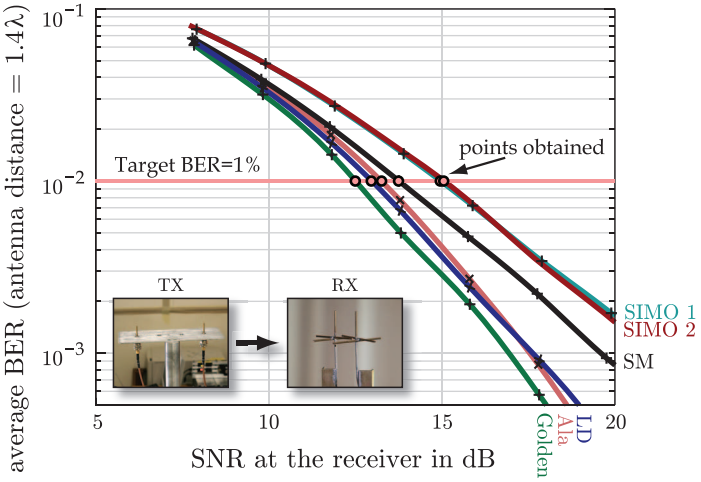

Figure 2. BER over SNR result for an antenna distance of $1.4\,\lambda$, same scenario as Figure 3 left.

III-E. Time Required for the Experiment

The measurement of a scenario takes about 10 hours, mainly because of the time needed to move the antennas. Another 10 hours are needed to process the 600 GB of baseband data samples received, in a cluster of 15 PCs by MATLAB.

IV. RESULTS

In total, 21 different scenarios were measured, within a timeframe of two weeks, in and between different floors of an office building. Surprisingly, the measurement results presented in the following did not change essentially between the different scenarios. We therefore only present the results of two representative scenarios (Scenario 1 and Scenario 2) to point out the key observations (see Figure 3):

- At not too closely spaced antennas (<0.2 to $0.4\,\lambda$ depending on the scenario), the Golden Code outperformed all the other transmission schemes, which

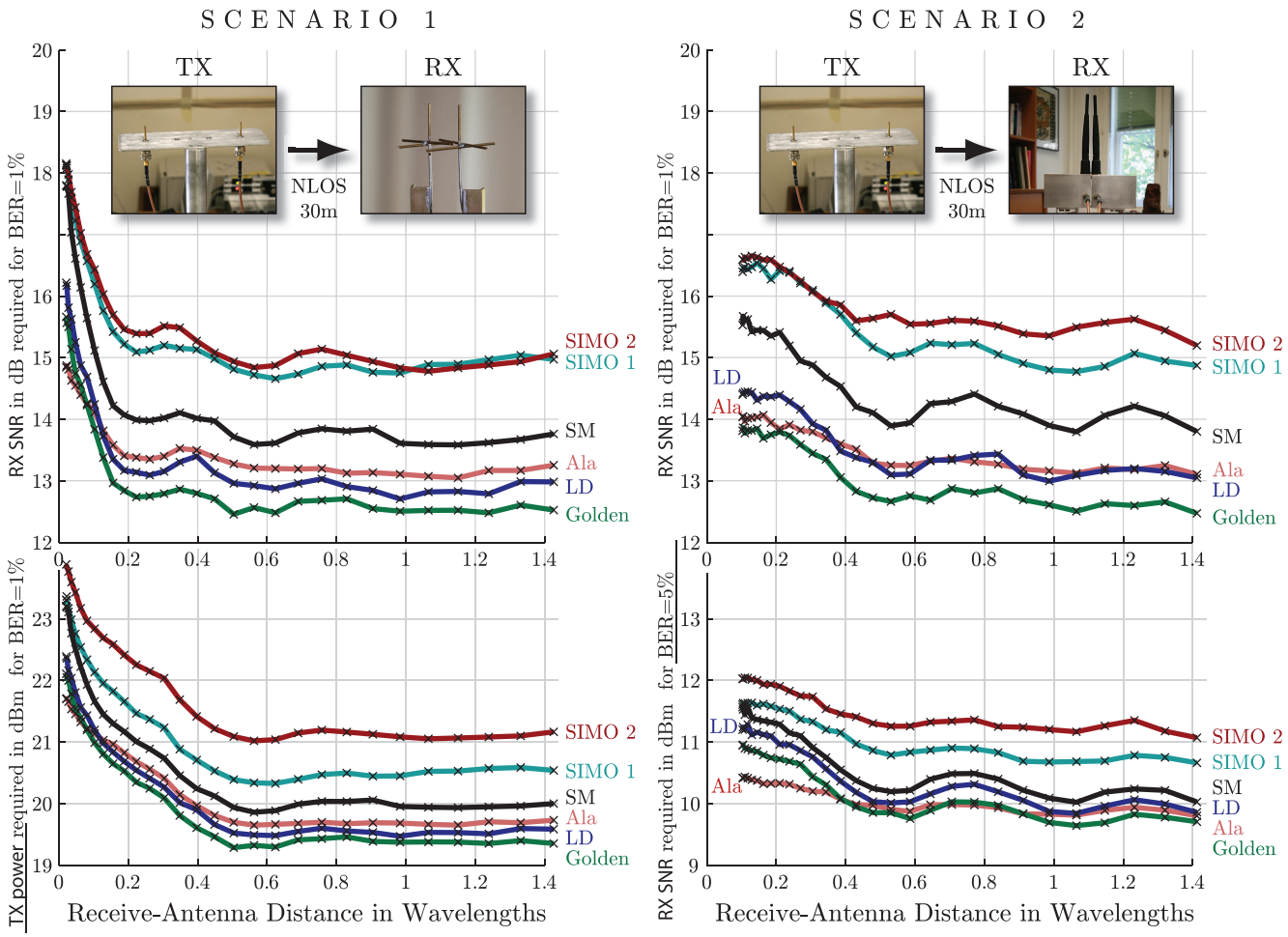

Figure 3. Measurement results of two representative scenarios (different RX antennas used).

means that a smaller average SNR was required at the receiver to obtain an average BER of 1 %.

- Only at very small antenna distances, the Golden code was outperformed by the Alamouti code. Please note that the curve of the Alamouti code is crossing the other curves at antenna spacings lower than 0.4 λ.
- But even at not too closely spaced antennas (> 0.2 to 0.4 λ depending on the scenario), the Alamouti code still performs nearly as good as the Golden Code or the LD code.
- In all scenarios measured, the LD code and the Alamouti code showed about the same performance for antenna distances larger 0.4 λ.
- Using two transmit antennas instead of a single one always increased the performance significantly.
- If the black receive antennas used in the Scenario 2 were tilted slightly (to change the polarization), the performance did not degrade anymore for small antenna distances. In fact, with this tilt, the antennas could not be placed closely enough anymore to observe any performance decrease.
- Note, there is a huge difference, if the curves presented in Figure 3 are plotted using "average transmit power required for a BER of 1 %" instead of "average SNR required at the receiver for a BER of 1 %". Firstly because mutual coupling effects and antenna mismatch losses[1] attenuate the transmitted signal especially at very small antenna distances. Secondly, the average receive power at antenna one and antenna two differed by up to 4 dB, depending on the scenario.

V. CONCLUSION

We carried out a multitude of 2×2 MIMO measurements in different non line-of-sight indoor scenarios. For these

[1] For a fixed antenna distance, losses due to antenna mismatch can be eliminated by correctly matching the antennas. For variable antenna distances, this is not possible with reasonable effort.

scenarios we evaluated e.g. “the average SNR at the receiver required for a BER of 1 %,” to compare a SIMO transmission with different space time codes, namely: the LD code, the Golden Code, the Alamouti code, as well as Spatial Multiplexing.

It turned out that in comparison to the non optimal Alamouti code, the LD code and the Golden Code did not show a significant performance increase. For very small antenna distances, they even performed worse — and this at a substantially increased receiver complexity (e.g. sphere decoding is required).

VI. ACKNOWLEDGMENT

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