Capacity of Different MIMO Systems Based on Indoor Measurements at 5.2GHz

Hüseyin Özcelik[1], Markus Herdin[1], Helmut Hofstetter[2] and Ernst Bonek[1,2]
{hueseyin.oezcelik,markus.herdin}@tuwien.ac.at, hofstetter@ftw.at,
ernst.bonek@tuwien.ac.at
[1]Institut für Nachrichtentechnik und Hochfrequenztechnik
Technische Universität Wien
Gußhausstrasse 25/389, A-1040 Wien, Austria
[2]FTW, Forschungszentrum Telekommunikation Wien
Tech Gate Vienna, Donau-City-Strasse 1/3. Stock, A-1220 Wien, Austria

Abstract

We compared the average capacities of measured 8×8, 4×4 and 2×2 systems with fixed array size in an indoor office scenario at different receive positions. As expected, correlation either at the transmit or receive side is limiting the MIMO capacity. While the 2×2 system reaches mostly the capacity of an i.i.d. Rayleigh fading channel, the 4×4 and particularly the 8×8 system does not. When we tried to fit the capacity of the measured MIMO channel, based on the estimated receiver and transmitter correlation matrices, to a popular stochastic MIMO correlation model, considerable discrepancy arose.

1 Introduction

Multiple-Input multiple-output (MIMO) systems are promising candidates for very broadband wireless local area networks. Especially in indoor scenarios, most likely the major area of application of such networks, the number of scatterers is often assumed as very high leading to arbitrary high MIMO capacities, only limited by the number of transmit and receive antennas.

There exists already investigations on the influence of antenna spacing and the number of transmit and receive antennas on the MIMO capacity [1], [2]. However, since mobile terminals are limited in space, the antenna arrays cannot be arbitrarily large. This means we have a given maximum aperture, and therefore more antennas mean less antenna spacing and higher correlation.

In this paper we investigate to what extent a higher number of antennas leads to a higher capacity when the total aperture stays constant. Particularly, we compare the capacities of 8×8, 4×4 and 2×2 systems. Additionally, we tried to fit the measured capacity, based on the estimated receiver and transmitter correlation matrices, to a popular stochastic MIMO correlation channel model [3].

2 Measurement

2.1 Measurement Setup

For the measurements, we used the wideband vector channel sounder RUSK ATM [4] with a measurement bandwidth of 120MHz at a center frequency of 5.2GHz. At the receive side a 0.4λ spaced 8-element uniform linear patch array (ULA) with two additional dummy elements was used. Each single patch antenna had a 3dB beamwidth of 120^o and was consecutively multiplexed to the single receiver chain. At the transmit side, a monopole antenna was mounted on a 2D positioning table where the position was controlled by the channel sounder by means of two stepping motors. The monopole transmit (TX) antenna was moved to 20 possible x- and 10 possible y-positions on a rectangular grid with $\lambda/2$ spacing forming a virtual TX matrix *without* mutual coupling.

For each TX position the channel sounder measured 128 snapshots of the frequency dependent transfer function between the TX monopole and all receive (RX) antennas, where 193 equidistant frequency samples of the channel coefficients within the measurement bandwidth of 120MHz were taken. Altogether, this resulted in a (128×193×8×200) 4-dimensional complex channel transfer matrix containing the channel coefficients for each snapshot, frequency, RX and TX position. Since the measurement of the whole 4-dimensional channel transfer matrix took about 10 minutes, we took the measurements at night to ensure stationarity.

2.2 Scenario

The measurements were carried out in the offices of the *Institut für Nachrichtentechnik und Hochfrequenztechnik, Technische Universität Wien*. A number of different office rooms were measured, always with the TX antenna positioned at the same place in the corridor. For our evaluation we took only the measurements of a single room with the RX antenna placed at 8 different positions. This room was amply furnished with wooden and metal furniture and plants, without line of sight to the TX (Figure 1). The door to this room was open.

3 Data Evaluation

3.1 Generating Different Channel Realizations

We compared the average capacities of 8×8, 4×4 and 2×2 MIMO systems. Since the correlation of both, the receiver and the transmitter influences the capacity, a fair comparison of these systems can only be done for antenna arrays (ULAs) with comparable apertures. For this reason, our 8×8 system consisted of 8-element ULAs

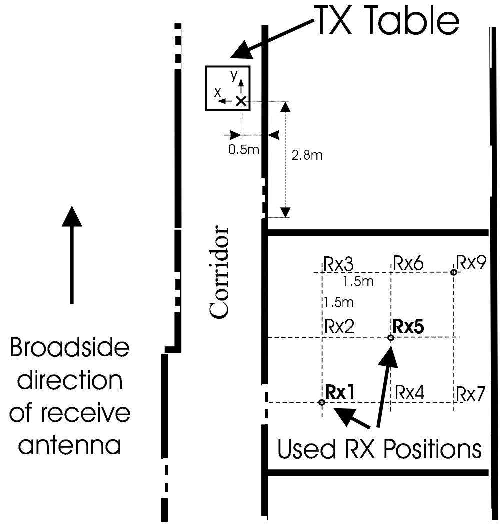

Figure 1: Floor plan of the corridor and office rooms

with 0.5λ (0.4λ) antenna spacing, the 4×4 system of 4-element ULAs with λ (0.8λ) spacing and the 2×2 system of 2-element ULAs with 3.5λ (2.8λ) spacing, at TX (RX). Therefore, the 2×2 system and the 8×8 system have an aperture of 3.5λ (2.8λ) and the 4×4 system of 3λ (2.4λ) at TX (RX).

Before we generated the MIMO channel realizations for these systems, we averaged over all 128 snapshots to increase the SNR leading to an 8×200 MIMO matrix for each frequency bin. The 200 TX positions were now used to create different spatial realizations of the considered systems. In case of the 8×8 system we used all RX antennas and took 8 adjacent TX positions in x-direction out of the 20×10 TX matrix. This virtual 8-element TX ULA was moved over all possible TX antenna positions resulting in $13 \cdot 10 = 130$ spatial realizations of the 8×8 MIMO channel matrix.

Our 4×4 system is based on the spatial realizations of the 8×8 system, but we just took only every second antenna element at both the transmit and receive side, resulting in an antenna spacing of λ and 0.8λ, respectively as mentioned before. The 2×2 system was generated analogously, i.e. we took every seventh antenna element at both ends, resulting in an antenna spacing of 3.5λ and 2.8λ, respectively.

Since we have measured the MIMO channel matrix at 193 different frequencies, this gives us in total $130 \cdot 193 = 25.090$ different realizations of the channel matrix to average over.

3.2 Capacity, Normalization and Correlation

For the capacity calculation we used the equation [5]

$$C = \log_2 \det \left(\mathbf{I}_\mathrm{n} + \frac{\rho}{\mathrm{n}} \mathbf{H}\mathbf{H}^H \right) \tag{1}$$

which gives the capacity when the channel is not known at the transmitter. Here $\mathbf{I}_\mathrm{n}$ is the $n \times n$ identity matrix, ρ the average receive signal to noise ratio (SNR), n the number of transmit and receive antennas and $\mathbf{H}$ the MIMO channel matrix. The superscript H stands for Hermitian transposition.

Since the measured MIMO matrices include the pathloss we had to do a normalization to set the average receive SNR to a specific value. For each system and each RX position, this was done by setting the equivalent SISO pathloss as defined by

$$\frac{1}{n^2} \sum_{i=1}^{n} \sum_{j=1}^{n} |h_{ij}|^2 \tag{2}$$

in average over all spatial and frequency realizations to zero dB. Here h_{ij} is the corresponding MIMO channel matrix element.

In addition to capacity, we also considered the *correlation* at both the transmit and receive side. To estimate the receive and transmit correlation matrix we used

$$\hat{\mathbf{R}}_\mathrm{rr} = \frac{1}{\mathrm{N}} \sum_{\mathrm{r}=1}^{\mathrm{N}} \mathbf{H}(\mathrm{r})\mathbf{H}(\mathrm{r})^\mathrm{H} \tag{3}$$

$$\hat{\mathbf{R}}_\mathrm{tt} = \frac{1}{\mathrm{N}} \sum_{\mathrm{r}=1}^{\mathrm{N}} \mathbf{H}(\mathrm{r})^\mathrm{H}\mathbf{H}(\mathrm{r}) \tag{4}$$

where N is the number of channel realizations, in our case 25.090, and $\mathbf{H}(r)$ the r*th* channel realizations.

3.3 Stochastic MIMO Correlation Model

Whether if the correlation is sufficient to describe the measured MIMO capacity in our scenario, we considered a simple stochastic MIMO model (Kronecker model, [3], [6]) based on the transmitter and receiver correlation:

$$\tilde{\mathbf{H}} = \mathbf{R}_\mathrm{rr}^{1/2} \mathbf{G} \mathbf{R}_\mathrm{tt}^{1/2}. \tag{5}$$

Here $\mathbf{R}_\mathrm{rr}$ and $\mathbf{R}_\mathrm{tt}$ are the receiver and transmitter correlation matrices and $\mathbf{G}$ is a matrix with independent identically complex Gaussian distributed (i.i.d.) elements with mean power of unity. Using this model and the estimated correlation matrices, we generated a set of 1000 different $\mathbf{H}$ matrices, normalized them as the measured channel matrices and compared the resulting capacities for both measured and synthesized channel matrices.

4 Results

Figure 2 shows both the average MIMO capacity of the measured (solid lines) and an i.i.d. Rayleigh fading (dotted lines) channel for a 8×8, 4×4 and 2×2 system for receive position Rx5. Whereas the measured 2×2 system nearly reaches the average capacity of the i.i.d. case, the 4×4 and particularly the 8×8 system suffer a strong loss in capacity. There is no linear increase of the capacity with the number of transmit and receive antennas. The higher the number of antennas is, the higher is the loss in capacity compared to the i.i.d. Rayleigh fading case.

The reason for this behavior can be found in the receive antenna correlation (Figure 3). Note that the estimated correlation matrices (equation (3) and (4)) contain also the average receive power in the main diagonal.

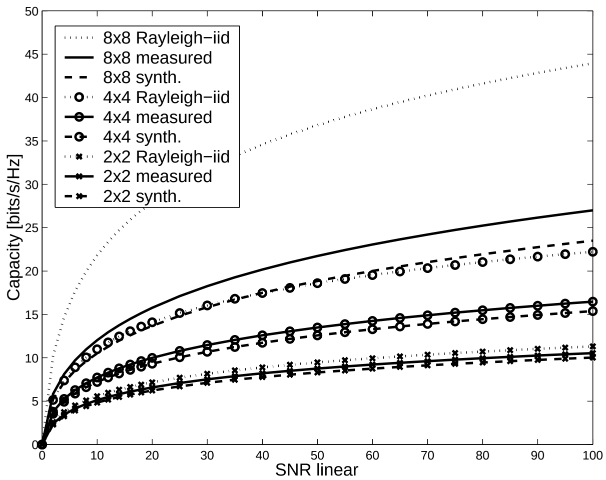

Figure 2: Average MIMO capacity vs SNR for receive position Rx5

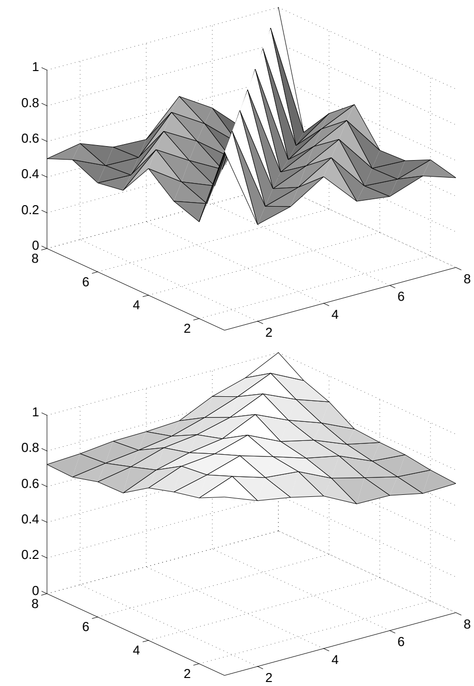

Figure 3: Transmitter (top) and receiver (bottom) correlation matrix for receive position Rx5

Therefore we looked at the normalized cross-correlation between all antenna elements to compare the antenna correlations for different receive positions. The cross-correlation coefficient between the i*th* and the j*th* receive antenna is given by:

$$r_{ij} = \frac{\sum_{r=1}^{N}\sum_{k=1}^{n} h_{ik}(r)h_{jk}(r)^*}{\sqrt{\left(\sum_{r=1}^{N}\sum_{k=1}^{n}|h_{ik}(r)|^2\right)\left(\sum_{r=1}^{N}\sum_{k=1}^{n}|h_{jk}(r)|^2\right)}} \quad (6)$$

Adjacent RX antenna elements have correlation values up to 0.95, which means they are nearly totally correlated. At the transmit side, we reach correlation values of adjacent antenna elements of up to 0.7. For the 4×4 and the 2×2 system the correlation becomes lower since we have only every second or every fourth transmit and receive antenna as compared to the 8×8 system. Although the RX correlation values for the 2×2 system are as high as 0.7, we reach nearly the i.i.d. capacity.

To see whether the stochastic MIMO correlation model (5) is able to give an accurate prediction of the MIMO capacity, we synthesized different realizations of the channel matrix based on the estimated correlation matrices. Again, we did this for 8×8, 4×4 and 2×2 systems and compared the resulting average MIMO capacity to the average capacity of the *measured* channel (Figure 2). As can be seen, the MIMO capacity calculated from the stochastic MIMO channel model is always an underestimate for the capacity estimated directly from the measurements.

Another interesting case can be observed at receive position Rx1. We notice that only adjacent receive antennas are highly correlated. Therefore the 8×8 system faces a strong capacity decrease because of the correlated fading but the 2×2 and 4×4 systems behave like in i.i.d. Rayleigh channels, since only every fourth or every second receive and transmit antenna is taken.

The capacities of the synthesized channels are generally below the capacities of the measured ones, although there are also cases where they are nearly equal. It seems that i.i.d. entries of the fading matrix G are not always a good fit.

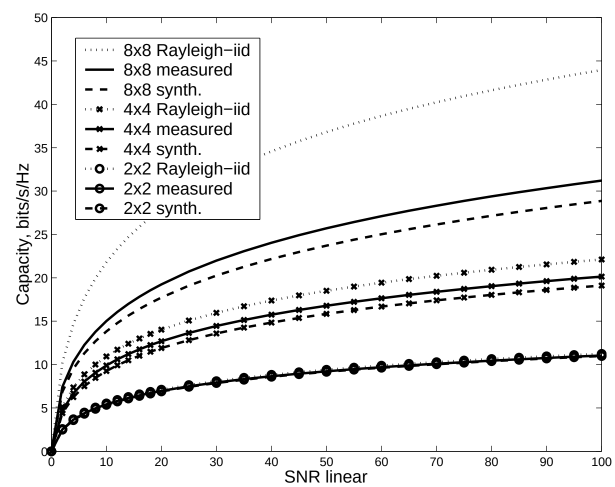

Figure 4: Average MIMO capacity vs SNR for receive position Rx1

5 Conclusion

With our measurements we compared the mean capacities of 8×8, 4×4 and 2×2 MIMO systems for a fixed antenna aperture. As expected, the correlation of the antenna elements are the limiting factor for the channel capacity. It can be seen, that the 2×2 system mostly reaches the i.i.d. Rayleigh case. The 8×8 system suffers strongly from the high correlation which mainly results from the small antenna spacing of $\lambda/2$ and 0.4λ, respectively.

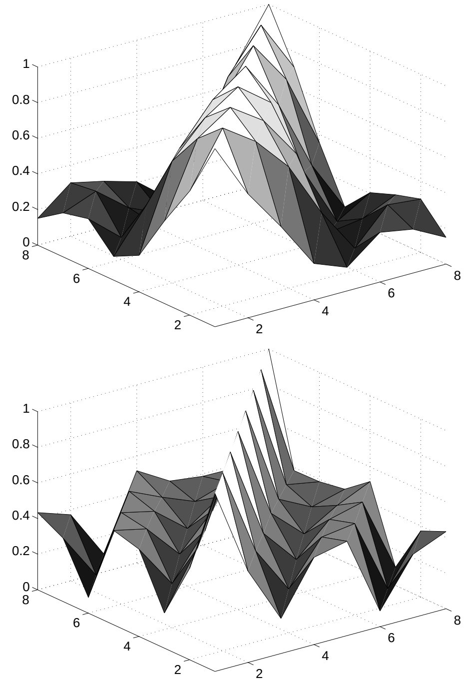

Figure 5: Transmitter (top) and receiver (bottom) correlation matrix for receive position Rx1

Our measurements do not support the stochastic model given in equation (5). In contrast, the mean capacities resulting from this model, based on the estimated correlation matrices, are generally smaller than the capacities estimated directly from the measurements. In some cases they are up to 15% below the measured capacity.

6 Acknowledgment

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