MEASURED MIMO CAPACITY ENHANCEMENT IN CORRELATED LOS INDOOR CHANNELS VIA OPTIMIZED ANTENNA SETUPS

Andreas Knopp, Mohamed Chouayakh, Robert Schwarz and Berthold Lankl

Department of Electrical and Electronics Engineering, Institute for Communications Engineering, Munich University of the Federal Armed Forces, 85579 Neubiberg, Germany

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Abstract: Our premise in this paper is to investigate the available channel capacity of MIMO systems in correlated transmission channels for various antenna arrangements differing in their suitability in order to construct high - rank LOS channels. Hence, a measurement campaign with a fast 5×5 - MIMO channelsounder was carried out in a typical, medium - scale, in - room office scenario giving the opportunity to virtually evaluate the channel capacities for arbitrary $M \times N$ - MIMO systems ($\{M, N\} \leq 5$) by antenna selection and combination. We use linear antenna arrays and vary their initial antenna spacings and orientations relative to each other which coincides with LOS channels of varying rank. In the sequel the measured capacities are compared giving an idea on the usefulness of the high - rank LOS channel construction in the presence of strong reflections. For our purpose we introduce an appropriate power normalization of the channel transfer matrix to exclude further effects on the capacity, as for example SNR variations due to varying transmitter - receiver distances, and only concentrate on the phase angle relations within the matrix. The results show a measurable benefit in channel capacity when such optimization and normalization is performed, especially for small antenna numbers.

1 INTRODUCTION

Multiple Input - Multiple Output (MIMO) transmission systems promise high channel capacity gains and reliability improvements for fixed bandwidth and transmit power (Telatar, 1995),(Foschini and Gans, 1998). In the context of the system design it is inevitable to be able of predicting the accessible channel capacity. Especially indoor transmission channels and as a subgroup in-room channels, where transmitter (Tx) as well as receiver (Rx) are located within the same room, are totally different from common statistical modelling approaches due to their strong Line - Of - Sight (LOS) signal component in coincidence with low mobility. In the narrowband case such correlated channels have been shown to typically provide only low MIMO outage capacities, particularly for small antenna spacings relative to the Tx - Rx distance (Vucetic and Yuan, 2003), (Molisch, 2005). Contrarily, theory offers the possibility to enhance the MIMO capacity of correlated channels by adapted antenna arrangements that are suitable for constructing high - rank LOS channels, e.g. (Bohagen et al., 2005). These approaches explore full MIMO capacity for fixed antenna positions as long as there are no reflected waves impinging at the Rx - two conditions that are hardly fulfilled in practice. On the one hand it is impossible to optimize the antenna setups for every position in the room and on the other hand the LOS signal never exists without reflections. Nevertheless we consider the LOS component being carrying most of the signal power. Therefore optimally chosen antenna setups which nearly can exploit the LOS component all over a particular room area should help to improve the channel's outage capacity even in the presence of reflections. This approach will particularly be probed in the sequel. Hence, in section 2 a channel description is provided and the capacity calculation is described. In section 3 we present our results from measurements as well as some preliminary insights derived from simulation. Last, we conclude the paper in section 4.

2 CHANNEL MODEL AND CAPACITY CALCULATION

General presumptions on the channel: In the context of MIMO applications and their capacity the in-

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door WLAN channel is commonly statistically modelled, where the modelling approaches concentrate on the NLOS transmission paths forming numerous and variously reflected waves ("rich scattering"). To fulfill these assumptions the LOS component must be distinctly attenuated by shadowing effects or when assuming high reflection factors $\xi^2 \approx 1$ the path lengths of the reflected waves must be in the range of the LOS path length. In this case the propagation loss of direct and reflected signal components range in the same order of magnitude and hence the reflection's impact rises. Usually those assumptions are less valid for in - room scenarios than for outdoor transmission with large distances between Tx and Rx. Therefore a similar modelling strategy is regularly performed in mobile communications. When in addition narrow transmission bandwidths are presumed the channel can be treated flat and information is provided only on the magnitude level distribution which especially in the case of high mobility can be modelled by a Rayleigh process (Paetzold, 2002). In this case the entries of the channel transfer matrix are assumed to be uncorrelated, zero mean, i.i.d. complex Gaussian random variables, a case which describes a convenient transmission channel for MIMO applications as the expected value of its capacity is high (Telatar, 1995) as long as the receive signal correlation is kept low. According to (Jakes, 1974) the latter condition can be achieved by antenna spacings of at least about half - wavelength ($\lambda/2$) what therefore has become a common design issue for MIMO antenna arrays. When the direct LOS signal component gets present this fact can be incorporated leading to the well known Rice propagation model (Paetzold, 2002). This statistical approach is widely used when discussing early indoor transmission systems and it is included in the popular, cluster based channel model introduced by Saleh (Saleh and Valenzuela, 1987).

Contrarily, in the case of the in - room propagation scenario discussed in the sequel a dominant LOS signal component that carries most of the energy is always present which in the consequence leads to correlated signals at the receiver inputs. Of course also in indoor scenarios the LOS signal component ist sometimes obstructed and therefore diffracted by objects but it is known from the theory of diffraction that no significant losses arise as long as the obstructing obstacle's size stays below the first Fresnel zone's dimension. For a typical WLAN center frequency of 2.4 GHz and distances of 2 m and 3 m between the obstacle and the Tx and Rx, respectively, the size of the first Fresnel zone is about 80 cm in diameter which is large compared to typical furniture or persons. Besides, one set of antennas (Tx or Rx) is typically mounted at the ceiling which distinctly reduces the risk of obstruction. In these scenarios the simple approach of a $\lambda/2$ antenna spacing is no longer sufficient as it theoretically can not exploit the maximum MIMO capacity with respect to LOS. By geometrically optimizing the antennas' positions and spacings at Tx as well as Rx resulting in proper phase angle relations among the entries of the channel transfer matrix, it is possible to make accessible the maximum MIMO capacity even in the case of correlated channels. Coinciding it is inevitable that the LOS signal component never exists without reflections which can hardly be included in any strategy of constructing high - rank channel transfer matrices. Obviously this effect gets more eminent when the power contributed by reflections rises as it is the case for declining room dimensions. Before we answer the question to what extent the high - rank LOS channel construction enhances the capacity in such real - world scenarios the theoretic background in terms of channel modelling and capacity calculation is summarized.

Capacity calculation: Contingent upon the considered transmission bandwidth our measurements cover the case of nearly frequency flat channels. Nevertheless, a frequency selective channel model should be assumed because it also includes the frequency flat channel as a special case and it is necessary for our way of evaluating the measured results as it will be explained in the sequel. According to our presumptions mentioned above we consider the following, widely deterministic description of the MIMO transmission channel. For a single input - single output (SISO) frequency selective, deterministic transmission channel the equivalent baseband channel transfer function for the time invariant case is given by

$$H(f) = \sum_{k=0}^{K-1} a_k \, \mathrm{e}^{-j2\pi f \tau_k} \; = \; \sum_{k=0}^{K-1} a_k \, \mathrm{e}^{-j2\pi \frac{L_k}{\lambda}}, \quad (1)$$

where the sum is evaluated over the K different transmission paths consisting of $K-1$ reflected signal parts and the LOS signal component is incorporated by the index $k = 0$. The complex amplitude factor a_k includes the phase information ϕ, the path - loss as well as the power - loss due to the reflection factor ξ^2, i.e. $a_k = \frac{\xi\lambda}{4\pi L_k} \mathrm{e}^{j\phi}$. The time τ_k denotes the signal part's delay for the particular transmission path which is clearly linked to its path length L_k by the speed of light c_0, i.e. $\tau_k = L_k/c_0$. The right part of the equation additionally introduces $H(f)$ depending on the wavelength λ. For a non - mobile scenario a_k and τ_k are mainly constituted by the location's geometry, i.e. primarily by the Tx's and Rx's positioning within the room as well as their arrangement in relation to the main reflection layers like walls, bottom, ceiling or large scale objects. With increasing mobility it is more and more appropriate for the channel to be modelled by some statistical process. In the observed scenarios described in this paper the amount of mobility is kept low and therefore no statistical modelling over time is performed.

Applying equation (1) to the MIMO case, for a time invariant frequency selective $M \times N$ - MIMO system consisting of N transmit and M receive antennas the vector of receive signals $\boldsymbol{y}(t) \in \mathbb{C}^{M\times 1}$ is calculated by an inverse Fourier transform of the spectrum of the transmit signal vector $\boldsymbol{X}(f) \in \mathbb{C}^{N\times 1}$ multiplied by the frequency selective channel transfer matrix $\boldsymbol{H}(f) \in \mathbb{C}^{M\times N}$, i.e.

$$\boldsymbol{Y}(f) = \boldsymbol{H}(f)\,\boldsymbol{X}(f) + \boldsymbol{\Upsilon}(f), \tag{2}$$

where $\boldsymbol{\Upsilon}(f) \in \mathbb{C}^{M\times 1}$ denotes the spectral vector of the additive noise $\boldsymbol{\eta}(t)$. The noise is assumed to be zero-mean complex Gaussian with covariance matrix $\mathbf{R}_{\boldsymbol{\eta}} = \mathrm{E}[\boldsymbol{\eta}\boldsymbol{\eta}^{\mathrm{H}}] = \sigma_{\eta}^2 \boldsymbol{I}_M$, where $\boldsymbol{I}_M \in \mathbb{C}^{M\times M}$ denotes the identity matrix and $\sigma_{\boldsymbol{\eta}}^2$ is the noise power at each receive antenna. Here each entry $H_{mn}(f)$ in $\boldsymbol{H}(f)$ has the structure of equation (1) whereas the values K and hence, a_k and τ_k differ.

According to (Telatar, 1995) and (Foschini and Gans, 1998) when uncorrelated transmit signals are presumed the time invariant channel capacity for a frequency selective MIMO - channel in the absence of channel knowledge at the transmitter is calculated from

$$C = \int_B \log_2\left[\det\left(\boldsymbol{I}_M + \frac{\sigma_{\boldsymbol{x}}^2}{\sigma_{\boldsymbol{\eta}}^2}\boldsymbol{H}(f)\boldsymbol{H}^{\mathrm{H}}(f)\right)\right] df, \tag{3}$$

where B denotes the transmission bandwidth, $\boldsymbol{I}_M \in \mathbb{C}^{M\times M}$ is the identity matrix, $\sigma_{\boldsymbol{x}}^2$ denotes the mean transmit power that is allocated to each transmit antenna. Furthermore $(.)^{\mathrm{H}}$ abbreviates the complex conjugate transpose. When the overall bandwidth is partitioned into sufficiently narrow, say S, segments each segment can be treated frequency flat and the integral of equation (3) reduces to a sum over the segments' capacity contributions, i.e.

$$C = \frac{B}{S}\sum_{s=1}^{S} \log_2\left[\det\left(\boldsymbol{I}_M + \frac{\sigma_{\boldsymbol{x}}^2}{\sigma_{\boldsymbol{\eta}}^2}\boldsymbol{H}[f_s]\boldsymbol{H}^{\mathrm{H}}[f_s]\right)\right]. \tag{4}$$

Equation (4) is used for the capacity calculation from measured data samples in section 3. From equations (3) and (4) it can be observed that the capacity is optimized by finding the optimal matrix entries in the channel transfer matrix $\boldsymbol{H}(f)$ dependent upon the frequency f. When only a LOS signal component is present this can be resolved by geometrically optimizing the antennas' position such that a high - rank channel transfer matrix is obtained. Several early suggestions from different authors, e.g. (Driessen and Foschini, 1999), were made for the construction of these channels but all of them suffer from the drawback that due to mathematical restrictions they are limited to only a small number of antennas. Furthermore the resulting geometric setups are often improper for practical applications as in the consequence the antennas have to be positioned far from each other all over the room. A recent and most general solution which overcomes the drawback of limited antenna numbers can be found in (Bohagen et al., 2005) where the authors present a strategy for the design of linear antenna arrays which under weak presumptions leads to a channel transfer matrix close to full - rank.

Additionally a very simple example which illustrates a possibility to optimize the channel capacity even in deterministic correlated MIMO channels in the case of a flat fading for a fixed location of Tx and Rx can be found in (Knopp et al., 2005). Of course in practice such optimization would have to be performed for every possible location what is far from realizability. Despite this fact the simple example and further analysis that have been performed in advance of our measurements, e.g. the deviation of the pure LOS capacity across a room of particular size for various antenna spacings, suggest that it is reasonable to generally enlarge the antenna spacings in order to better exploit the strong LOS signal component for possibly large areas of a room without taking into account reflections. The arising question to what extent the antenna setup's simplified optimization for LOS via enlarged but fixed antenna spacings all over the room even in conjunction with reflections stays still profitable is discussed in section 3.

3 RESULTS

3.1 Scenario Description and Method of Measurement

For the channel measurements we used a 5×5 MIMO channelsounder with a bandwidth of 80 MHz at a carrier frequency of 2.45 GHz endowed with $\lambda/2$ dipole antenna arrays positioned as equidistantly - spaced uniform linear arrays (ULAs). The maximum bandwidth ranges some factor above the typical bandwidths proposed for current and future indoor applications and hence, achieves a higher time resolution. The channel information was collected by sequentially deriving the entries of the channel transfer matrix, i.e. by collecting the complex baseband channel impulse responses (CIRs) and channel transfer functions (CTFs). A Perfect Squares - Minimum Phase (PS - MP) CAZAC sequence (Linde and Roehrs, 1993) was used as pilot signal, a discrete sequence with a frequency flat power spectrum and therefore a perfectly zero autocorrelation for different time instances. We used 196 pilot symbols and due to our sampling rate of 100 MHz we achieved a frequency resolution of 510 kHz ($196 \cdot 510$ kHz = 100 MHz), but for the capacity evaluation we reduced the considered bandwidth off line to 80 MHz by digital filtering. The measurement of one complete channel matrix consisting of 25 entries took about $160\ \mu$s. This measurement time is short enough by far to consider the channel invariant during that time, especially in the chosen scenarios with low mobility and it is much faster than even a single SISO network - analyser measurement which typically takes around 100 ms. A further advantage of the system is the fact that after measuring the 25 CIRs we are able to arbitrarily combine them in off - line mode and virtually built up different MIMO systems by antenna selection from the measured data, in fact $\binom{5}{M}\binom{5}{N}$ combinations are possible for an $M \times N$ MIMO system.

The measurements were taken within a modern office building constructed from steel and glass. We chose a typical medium - scale office or laboratory scenario which is depicted in detail in figure 1 providing all necessary information on the materials, dimensions and arrangements of the walls and the most important furniture. The room was equipped by typical of-

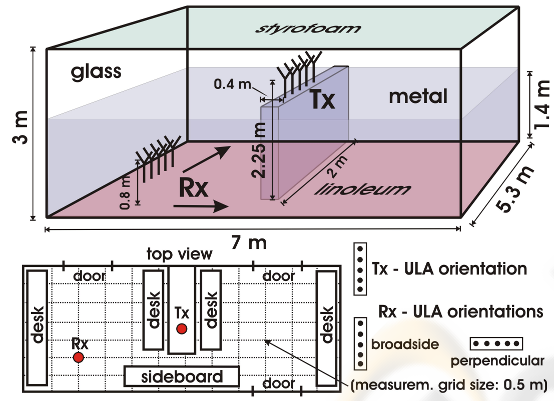

Figure 1: Schematics of the measured location.

fice working desks, i.e. wooden desks and chairs with metal legs. Additionally a metal bar was placed in the center of the room dealing as a divider. The Tx was arranged on top of that divider at height 2.25 m what supposes that in the context of in - room scenarios the Tx might reasonably be placed near the ceiling to guarantee a LOS link for every receiver position. The Tx position was kept fixed while the Rx was moved at typical working desk hight in two dimensions across the room along a grid. During one complete grid measurement the relative positions of the Tx and Rx antenna array were not changed and either broadside or perpendicular (see fig. 1). The mobility was kept low and therefore the statistical analysis of the measured data was performed in the spatial domain treating the Rx position as a random variable. The statistic was expanded by an additional evaluation of the 196 frequency segments of bandwidth 510 kHz which our sampled transfer function was partitioned into. We assumed every frequency segment being a realization of a possible narrow band transmission channel out of 80 MHz / 510 kHz = 156 possible transmission channels around the carrier of 2.45 GHz. From equation (1) it becomes obvious that the relation L_k/λ is the key parameter for the CTF's phase angle as well as its path - loss. Changing the Tx - Rx distances the value L_k is changed resulting in a different CTF. Changing the carrier frequency the wavelength λ is changed what also alters the CTF. Interpreting the variation of L_k/λ due to the change of λ as if λ was kept fixed and L_k was altered instead, the statistical evaluation of different frequency segments which are placed close to each other around the carrier can be interpreted as virtually moving the Rx within a small area. This strategy provides the possibility to enlarge our spatial statistics.

3.2 Mimo SNR Definition and Capacity Normalization

A crucial aspect when evaluating measured channel transfer functions in terms of the channel capacity is the definition of the signal to noise ratio in equation (3). Generally, we suggest a definition that best represents the physical reality of transmission systems with respect to their degrees of freedom for the user. Those are mainly the transmit power per transmit antenna $\sigma_{\boldsymbol{x}}^2$ and the noise power per receive antenna $\sigma_{\boldsymbol{\eta}}^2$ as the latter includes the receiver noise figure which depends on the chosen hardware. Of course with that definition the ratio $\sigma_{\boldsymbol{x}}^2/\sigma_{\boldsymbol{\eta}}^2$ does not meet the commonly used SNR definition ρ which describes the receive signal to noise ratio at the receiver input, but ρ clearly emanates from $\sigma_{\boldsymbol{x}}^2/\sigma_{\boldsymbol{\eta}}^2$ if it is multiplied by the channel's path loss ζ^2, i.e. $\rho = \sigma_{\boldsymbol{x}}^2/\sigma_{\boldsymbol{\eta}}^2 \cdot \zeta^2$. In our definition ζ^2 is completely incorporated in the channel transfer matrix which causes ρ at the receiver input being dependent upon the distance between Tx and Rx as well as the number and power of impinging waves. This approach does best represent physical reality as it focusses on the true capacity available in practice including all the relevant effects. To give an example: if the commonly investigated Non - LOS Rayleigh flat fading channel for a given value of ρ (which again denotes the resulting SNR at the receiver input) is considered, the capacity will be comparatively close to its maximum for that ρ. If now a strong LOS signal component is brought into the scene the value of ρ will be distinctly higher what rises the true channel capacity. If the rank of the channel transfer matrix for certain geometric antenna arrangements is observed, it will be close to rank = 1 for the LOS case and close to full - rank without the LOS. Nevertheless, if one concludes from the observation of the channels' ranks that the one with LOS present is worse for MIMO applications, this conclusion in most cases will be totally wrong as the SNR gain is ignored. The risk of such misinterpretation especially rises if the comparison of the two channels is performed by simply substituting ρ for $\sigma_{\boldsymbol{x}}^2/\sigma_{\boldsymbol{\eta}}^2$ and in addition normalizing the channel transfer matrix by an appropriate matrix norm to unit power for compensation, i.e. eliminating the path loss from the channel. If now the two power - normalized channels are compared for the same value of ρ, the Non - LOS channel will clearly outperform the LOS channel, a result which is far from the truth in most cases. Hence, we propose to avoid any normalization to evaluate different channels with respect to their effective channel capacity.

Nevertheless, if one's interest focusses on certain effects and their influence on the capacity it might be reasonable to eliminate all the further effects that affect the capacity besides. In this paper we concretely investigate the antenna arrangement's impact on the channel capacity what rather means that we want to find out how different antenna spacings can influence the channel matrix' rank in the presence of reflections. We perform a spatial statistics what coincides with varying Tx - Rx distances. As we do not want to take into account the variation of ρ due to those distance changes we therefore replace $\sigma_{\boldsymbol{x}}^2/\sigma_{\boldsymbol{\eta}}^2$ in equation (3) by ρ and keep its value fixed (in the sequel it is set to ρ = 30 dB), while we eliminate the path loss from the channel transfer matrix by normalizing it to unit power using the Frobenius matrix norm, i.e. $||\boldsymbol{H}||_{\mathrm{F}}^2 = 1$. This norm simply sums up the matrix entries' power and normalizes by that sum. The strategy is appropriate for our investigations but the reader should be aware of the given presumptions when interpreting the results. To give a physical interpretation, the used normalization is equivalent to permanently adjusting the Tx power in order to keep the Rx input power and therefore ρ fixed independently from the channel.

3.3 Evaluation of the Results

Preliminary simulations: To develop an idea of the reflections' impact on the outage capacity (OC)[1] before presenting our measured results we provide results from simulation. We simulatively obtained capacity cumulative distribution functions (CDFs) for a room with identic dimensions as our measurement location while considering the direct (LOS) signal component as well as the reflections from all the surrounding walls, the bottom and the ceiling. In the simplified simulation we included single, double, triple and quadruple reflections and calculated them by means from geometric optics using a spherical wave model but ignored further effects like diffraction, scattering and transmission through objects. The Tx was placed in the center of the room and the Rx was moved, both at a height of 1.5 m. The reflection factor was set to 0.3 what corresponds to an amplitude - loss of 10.5 dB, which describes a typical but comparatively high reflection factor for indoor materials what in the consequence slightly overestimates the reflection's power marking a worse case than practically expected. Similar to our measurements and in accordance to the description of subsection 3.1 the simulation was performed over a bandwidth of 80 MHz formed by narrowband frequency segments of 500 kHz and the results were statistically evaluated over a spatial grid as well as over those frequency segments. The capacities were calculated according to equation (4). Besides the normalization of the channel transfer matrix we furthermore normalized the capacity by min$\{M, N\}$ which is equivalent to the maximum linear capacity increase of an $M \times N$ - MIMO system. This normalization leads to capacities which are approximately independent from the number of antennas and therefore also eases comparability as the capacity CDFs lie within similar ranges of magnitude. The results for a 2×2 - MIMO system with different antenna spacings (equally chosen at Tx and Rx) are depicted in figure 2. For both antenna spacings 5 curves can be observed

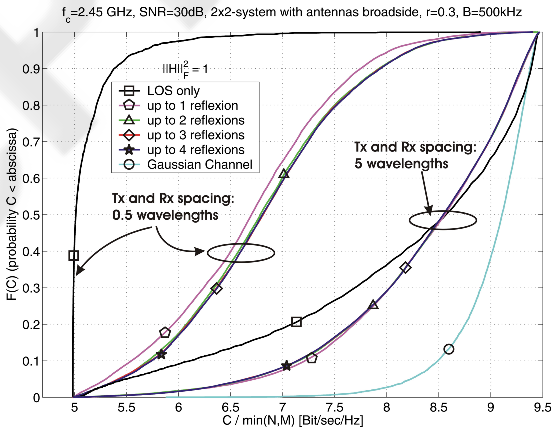

Figure 2: Simulated C-CDFs for different antenna spacings.

differing in the considered number of reflections. The legend entry "up to 2 reflections" for example denotes the case of considering the LOS signal part and all reflected waves which were reflected twice at maximum. For the usually chosen $\lambda/2$ spacing the CDF considering only the LOS signal part clearly indicates a very low capacity with low spatial variations what can be seen from the steepness of the curve. This can be understood from the fact that the channel trans-

[1] the x % outage capacity describes the capacity value which is NOT exceeded with a probability of x % (Vucetic and Yuan, 2003)

fer matrix is close to rank = 1 for that small antenna spacings nearly all over the room. Obviously when reflections are included the capacity increases, the 50 % OC for example is increased by about 35 % compared to its minimum for the 2×2 - MIMO system but the 10 % OC only slightly increases by about 15 %. Obviously the reflections help to increase the OCs by enhancing the channel transfer matrix' rank but compared to the case of a Rayleigh fading channel of identical power the capacity stays still low.

Contrarily, when the antenna spacing is enlarged what according to the example presented in the previous section coincides with enhanced utilization of the LOS component in terms of MIMO the 10 % OC for the pure LOS is increased already by over 20 % and the 50 % OC is even increased by about 72 %. Considering the reflections in addition the 10 % OC is further increased by 18 % while the 50 % value stays unchanged compared to the pure LOS case. From that OC onwards the reflections no longer increase the MIMO gain, contrarily from about the 50 % OC up they even reduce it. This supports the idea that in optimally configured systems with respect to LOS the reflections disturb the well adapted phase angle relations within the transfer matrix (see (Bohagen et al., 2005), (Knopp et al., 2005)) and therefore reduce the capacity although in the simulation only a negligible reduction can be observed. The low steepness of the pure LOS CDF in the large antenna spacing case shows the second problem of the optimization approach: any optimized antenna spacing only holds for a certain spatial region and can even correspond to the worst case outside that region. Therefore the spatial variation of the capacity for a fixed antenna spacing is high. Last, it is observed from the figure that in the low capacity case with a LOS channel transfer matrix close to rank = 1 its rank is already distinctly increased by only considering single reflections and for the case of double reflections a further capacity increase can be observed. If the LOS signal part is exploited well the reflections' influences on the capacity reduces meaning the better the LOS is exploited the more the capacity seems to be statistically dominated by LOS. Generally it appears to be sufficient in terms of the capacity if triple and quadruple reflections are neglected as their weak power contributions can not significantly change the capacity CDFs.

Measurements: Taking a look at the corresponding capacity CDFs obtained from measured data the basic results from the preliminary, simplified simulations are widely confirmed. It must be outlined in advance that the particular results (especially the measured values and numbers) are only valid for the chosen antenna spacings which were not particularly optimized to maximize the capacity all over the particular environment. We just used an arbitrary spacing

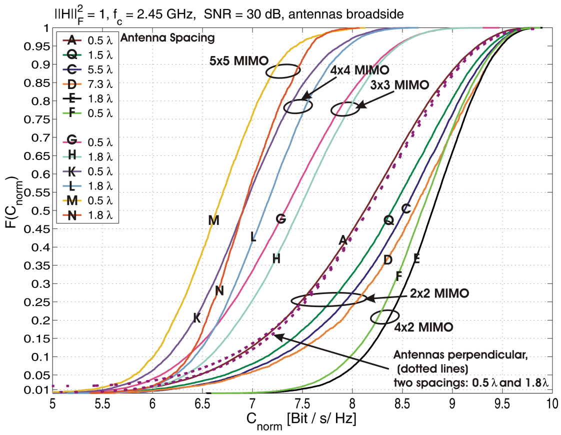

Figure 3: Measured C-CDFs for various settings.

larger than half - wavelength which was known to deliver local capacity maxima in terms of LOS (Knopp et al., 2005). We not especially tried to find the distinctly best choice with the most capacity maxima for the range Tx - Rx distances in the investigated room as we hold the opinion that such strategy is far from practice due to its complexity. So it is still possible to discover antenna spacings which even outperform and further stress the results presented next.

Firstly looking at the curves for the narrowband 2×2 - MIMO system it can be observed from figure 3 that for larger antenna spacings the 10 % OC for instance can be increased up to 10 %. In the contrary to the simulation for the 50 % OC the percentage increase is not even higher but slightly lower. On the other hand even in the $\lambda/2$ antenna spacing case which is badly conditioned for LOS the 10 % OC already reaches a value about 20 % above the simulation. This supports the assumption of the simplified simulation model being not thoroughly sufficient for capacity simulations as the receive power contributed by reflected and scattered waves seems to be higher than the model expects, say the scattering is somewhat richer than in the simulation at least in the medium - scale office scenario under investigation due to its well reflecting materials. This fact principally has to be regarded positive for the MIMO channel capacity as the impact of the LOS - exploitation decreases. Taking a look at the larger antenna spacings the curves are steeper in practice than for the larger antenna spacing in the simulation what states that in the case of nearly optimum antenna spacings with respect to LOS the reflections disturb the phase relations in the channel transfer matrix and reduce the matrix rank as it already was expected by theory. Hence, for the current scenario the optimization for LOS by choosing larger antenna spacings still enhances the OC whereas the capacity gain of about 10 % is comparatively low. If beyond the spacing enlargement the number of antennas at Rx and Tx is increased the normalized capacity gain is still observable but slightly decreases compared to the case of less antennas. The reason is found from the fact that the higher the antenna number the less the simplified approach of larger, equally chosen antenna spacings fits the optimal configuration for large areas of the room. So the curves in general shift closer to the minimum capacity whereas it must be considered that the real capacity without normalization still gets higher if the number of antennas is increased[2]. A further result which we obtain from the curves is the normalized OC increasing for asymmetric MIMO systems with a higher number of receive antennas as can be seen from the figure. This effect comes from the enhanced receive diversity which not only increases the receive power but also reduces the capacity's variation as the correlation of the receive signals is reduced. The curve steepness generally increases for higher number of antennas showing reduced capacity variations. A last modification is introduced by changing the antenna arrays' positioning towards each other from broadside to perpendicular. As it was shown in (Knopp et al., 2005) this configuration can hardly exploit the LOS component and therefore the LOS capacity part stays close to its minimum. This configuration is even worse than $\lambda/2$ antenna spacing and it is nearly completely independent from the antenna spacing. This result is widely confirmed by the measurements as the spacing enlargement hardly provides a capacity improvement. Here again the antenna setup's important impact is confirmed. To shortly summarize the results: as a rule of thumb the measurements suggest to use antenna spacings of a few wavelengths[3] and choose an asymmetric MIMO system with a higher number of Rx antennas than Tx antennas.

4 CONCLUSION

In this paper we showed by measurements that the antenna setup's adjustment at Rx and Tx in order to construct higher - rank LOS channels might be beneficial in practice. For the sake of simplicity and practical realizability we only worked with linear antenna arrays and chose a simplified optimization approach of changing the antenna spacings and the arrays' initial orientation relative to each other and we kept those parameters fixed for the measurements all over the room being aware that this proceeding is far from really optimizing the antenna's position for every measurement as proposed for example by (Bohagen et al., 2005). Despite such simplification we clearly could enhance the channel's outage capacity even though we had to cope with strong reflections and scattering effects disturbing the LOS signal part. Hence, we conclude that optimizing indoor MIMO systems by measures of low complexity for its powerful LOS signal component already is an appropriate procedure to enhance the available channel capacity of those correlated transmission channels. We furthermore expect the enhancing effect being even rising with increasing room dimensions as the reflected waves' power contribution decreases.

[2] remember that our curves in reality have to be multiplied by $\min\{M, N\}$

[3] The concrete value is dependent mainly on the dimension of the room

REFERENCES

Bohagen, F., Orten, P., and Oien, G. (2005). Construction and analysis of high-rank LINE-OF-SIGHT MIMO channels. In *Wireless Communications and Networking Conference, pp. 91-100*.

Driessen, P. and Foschini, G. (February 1999). On the capacity formula for multiple input-multiple output wireless channels: A geometric interpretation. In *IEEE Transactions on Communications, vol. 47, No. 2, pp. 173-176*.

Foschini, G. and Gans, M. (1998). On the limits of wireless comunications in a fading environment when using multiple antennas. In *Wireless Personal Communication, vol. 6, pp. 311-335*.

Jakes, W. (1974). *Microwave Mobile Communications*. John Wiley & Sons.

Knopp, A., Chouayakh, M., and Lankl, B. (2005). Capacity optimization and modelling of frequency selective WLAN indoor MIMO channels based on measured data. In *Proceedings of the Third IEEE SSD 05, Tunisia*.

Linde, L. and Roehrs, U. (June 1993). On a class of polyphase cazac sequences and their application in HF channel sounding. In *The Transactions of the Institute of Electrical Engineers, pp. 110-123*.

Molisch, A. (2005). *Wireless Communications*. John Wiley & Sons.

Paetzold, M. (2002). *Mobile Fading Channels*. John Wiley & Sons.

Saleh, A. and Valenzuela, R. (1987). A statistical model for indoor multipath propagation. In *IEEE J. Select. Areas Commun., vol. 5, pp. 128-137*.

Telatar, E. (1995). Capacity of multi-antenna gaussian channels. In *AT&T-Bell Technical Memorandum*.

Vucetic, B. and Yuan, J. (2003). *Space-Time Coding*. John Wiley & Sons.