MIMO — STUDY PROPAGATION FIRST!

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ABSTRACT

Despite many valuable contributions to the theory and practice of MIMO communication systems from various scientific fields, we want to emphasize the outstanding importance of propagation aspects when dealing with MIMO systems. Radio propagation forms the basis for any radio channel including MIMO systems. On the one hand, popular mathematical models and commonly applied statistical assumptions sometimes turn out to neglect important properties of MIMO radio channels. On the other hand, detailed knowledge and investigations of MIMO specific phenomena (e.g. keyholes) do not imply practical relevance. By means of four specific examples we argue that studying propagation is indispensable in order to stay in touch with real MIMO channels.

1. INTRODUCTION

Multiple-input multiple-output (MIMO) systems have attracted the interest of many researchers from a great variety of scientific fields including channel coding, information theory, signal processing, and others. Despite many powerful mathematical tools and important new insights, which have been developed by these scientific communities, we must not forget that the physical basis of MIMO systems is the propagation of radio waves. This paper aims at emphasizing the importance of studying propagation aspects when dealing with MIMO systems. We will illustrate our point by four examples taken from the world of MIMO systems.

To model MIMO channels in a realistic way, models have been created to incorporate channel correlation. A very popular model doing this is the so-called 'Kronecker' model [1]. There, the transmitter and receiver correlation properties are assumed to be independent and are modeled separately. Are these models accurate enough to describe realistic channels appropriately?

An interesting results of recent measurements is that MIMO capacity is mainly dominated by the average receive SNR. The multipath richness for different positions in a considered environment does not vary a lot [2, 3]. Is it sufficient to measure the multipath structure of just a single typical scenario in an environment in order to estimate the multipath richness of all other positions in this environment?

Aggregate statistical metrics are commonly used for characterizing MIMO channels. However, interpreting aggregate statistics according to common assumptions can be misleading, significantly different propagation environments can result in a similar aggregate metric. An important aspect in this respect is the size of the statistical ensemble. Which is the correct ensemble?

Only recently, the authors of [4] have identified the keyhole phenomenon. A channel model capable of modeling this has been proposed in [5] and the authors of [6] have created and measured a synthetic keyhole channel. However, reports of measured keyholes are very rare. Do we have to consider keyholes for channel coding or signal processing, or can we discard them as irrelevant?

2. MIMO CHANNEL MODELING

The simplest approach for MIMO channel modeling is to assume an i.i.d. complex Gaussian fading MIMO channel that provides both large capacity and diversity. This is a common assumption for simulating space-time codes but has the disadvantage that the results are not related to what can be achieved in a real scenario. Actually, correlations at both Rx (receiver) and Tx (transmitter) are very likely to exist because of limited angular spread and dominant directions of arrival or departure. To account for this it is necessary to include the correlation of the channel matrix elements in a proper way.

A very popular approach is the so-called 'Kronecker' model as presented in [1]. The basic idea is to generate a correlated Rayleigh fading channel matrix $\tilde{\mathbf{H}} \in C^{m \times n}$ according to

$$\tilde{\mathbf{H}} = \mathbf{R}_{\mathrm{Rx}}^{1/2} \mathbf{G} \left(\mathbf{R}_{\mathrm{Tx}}^{1/2} \right)^{\mathrm{T}} , \qquad (1)$$

where $\mathbf{R}_{\mathrm{Rx}}$ and $\mathbf{R}_{\mathrm{Tx}}$ are the correlation matrices at the Rx and the Tx link end; and $\mathbf{G}$ is a random fading matrix with i.i.d. random entries.

As a result, the correlation properties of the Tx and the Rx side are completely decoupled. Beside simplified analytical treatment or simulation of MIMO systems, this assumption allows for independent array optimization at Tx and Rx. Therefore, and because of the simplicity of the model, it has become popular.

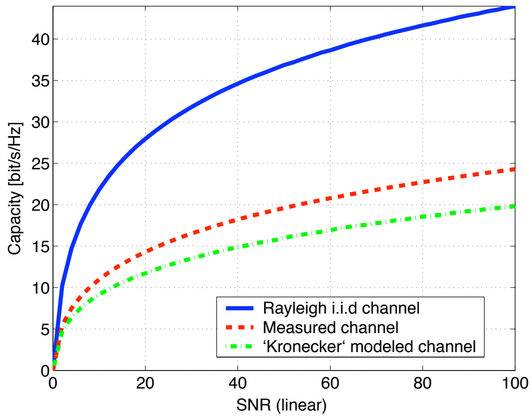

Fig. 1. Estimated capacity for Rayleigh i.i.d, measured and synthesized channel, RX position Rx13, direction D1

However, how accurate are the mentioned channel modeling approaches, i.e. using an i.i.d. channel or the 'Kronecker' model, compared to real measurements? Considering a rather typical indoor scenario [7] with dominant paths, Figure 1 shows the average MIMO capacity for synthesized data using either the i.i.d. model or the 'Kronecker' model and for the measurement data itself. It becomes clear that an i.i.d. model (solid blue line) largely overestimates the available MIMO capacity, but also the 'Kronecker' model (dash-dotted green line) does not accurately reproduce the MIMO capacity; it underestimates the capacity significantly.

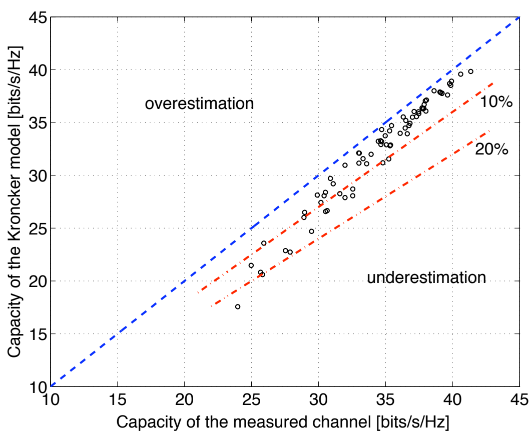

Fig. 2. Scatter plot of average 'Kronecker' model capacity vs. average capacity of measured channel for an 8×8 MIMO system

In Figure 2 the capacities for measured channel and synthesized channel for all available indoor MIMO measurements in the mentioned environment are shown. Here, it can be seen that the mismatch of the 'Kronecker' model for the considered scenario is not a single case but that it underestimates the capacity systematically. It is, therefore, necessary to perform more detailed measurements and propagation studies in order to create advanced MIMO channel models that are able to model different environments and even different locations in a specific environment adequately [8].

3. MIMO CAPACITY, SNR, AND MULTIPATH RICHNESS

An often considered question is what is more important to achieve high MIMO capacities: a large SNR or a 'good' MIMO channel in terms of high multipath richness and therefore low correlation. Measurements showed [2, 3] that a high average receive SNR is the most important factor to reach high MIMO capacity, typically the influence of the multipath richness is much lower than the influence of the SNR. It is even possible to approximate the average MIMO capacity for different scenarios within a specific environment by just taking the measured channel matrices from a typical scenario and adapting the receive SNR to the actual receive SNR for any other considered scenario within this environment. This is shown in Figure 3.

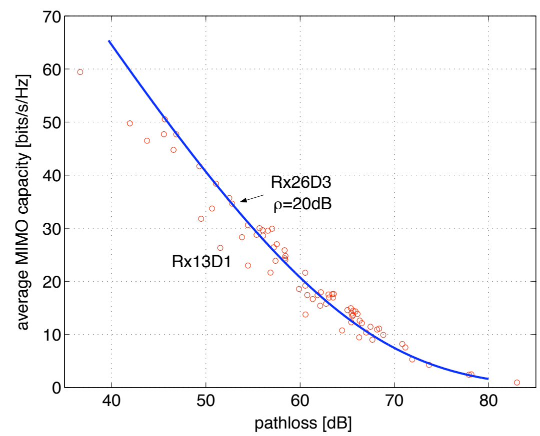

Fig. 3. MIMO capacity for different scenarios in an indoor office environment vs. pathloss

There, the average MIMO capacities for all available receive positions and directions (i.e. all scenarios) in an indoor office environment [7] are plotted vs. the average pathloss for each scenario. All measured channel matrices were normalized by the same factor such that for scenario Rx26D1 the average receive SNR was equal to 20dB and for all other scenarios different according to the respective pathloss. This means that the effect of the pathloss was included in the capacity calculation. Additionally, the MIMO capacity for Rx26D1 is shown (solid blue line) when the pathloss and therefore the average receive SNR is varied artificially.

For the major part of scenarios, the MIMO capacity can be approximated by the blue line, i.e. by calculating the MIMO capacity from the measured MIMO matrices of a typical scenario where just the pathloss and therefore the average receive SNR was adapted accordingly. However, first of all it is hard to decide which scenario is typical when only measuring at one position and second there are still some scenarios where exceptional behaviour can be observed. To understand what is happening, propagation has to be studied and comprehensive measurements have to be done.

4. AGGREGATE STATISTICS

Aggregate statistical metrics, like e.g. fading statistics or probability density functions (pdf) of capacity values, are a commonly utilized means for characterizing mobile radio channels. Fading statistics, for example, allow some conclusions w.r.t. to the propagation environment. Rice fading is typically associated with a LOS (line of sight) component; double-Rayleigh fading has been reported to occur in environments with cascaded scatterers [9]. However, interpreting aggregate statistical metrics according to common assumptions and rules of thumb can be misleading. As a consequence, studying the propagation aspects of a radio environment is necessary for a thorough understanding of statistical results.

In order to illustrate our argument, we present statistical evaluations of the previously mentioned indoor MIMO measurements, where the details of the measurement can be found in [7]. The Rx antenna was a uniform linear array of eight printed dipole elements; at the Tx link end we applied a single monopole antenna mounted on a positioning table. The Tx antenna was moved on a regular grid (spacing of half the wavelength) over the area of the virtual Tx array (a rectangular of size 10×5 wavelengths). In the frequency domain, 193 samples over a bandwidth of 120MHz were taken. The measured channel coefficients form a data array of size 193 (frequ.) × 8 (Rx) × 200 (Tx).

As an aggregate analysis of the fading statistics, we took all channel coefficients over space and frequency, normalized the mean power to unity, and calculated the corresponding pdf of envelope amplitudes. The result, depicted in Figure 4, shows a fading behaviour between Rayleigh and double-Rayleigh. This suggests that the radio environment has no LOS component and cascaded scattering plays a significant role.

A more detailed analysis changed the interpretation completely. For each Tx position, we calculated the mean power over 193 frequency samples and 8 Rx antennas. It turned out that the mean power is not constant over the area of the Tx array but it varied significantly. Dividing the virtual Tx array into two distinct and contiguous areas we found out that the first subset of Tx positions had low power and covered two thirds of the whole array, whereas the power of the second subset covering the other third of the Tx positions was higher by 6.1dB. Again, we calculated the pdf of the envelope amplitude of the channel coefficients of both subsets

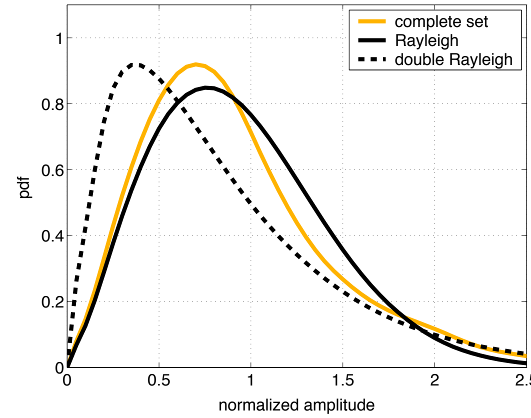

Fig. 4. PDF of measured envelope amplitudes in comparison with the Rayleigh and double-Rayleigh distributions. The statistical ensemble comprises the entire measurement set.

(the normalization to unit power was performed separately for the two subsets). The result can be seen in Figure 5. Both subsets clearly show a Ricean behaviour indicating a LOS component. The first subset has a Ricean K-factor of 1.06, for the second subset the Ricean K-factor is 2.06. The observed difference between the double-Rayleigh behaviour of the entire ensemble and the Ricean fading of the subsets is solely due to different sizes of the averaging region.

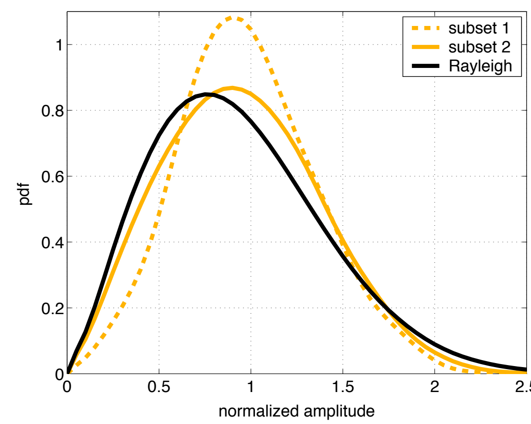

Fig. 5. PDF of measured envelope amplitudes in comparison with the Rayleigh distribution. The measured data was divided into two distinct subsets yielding two statistical ensembles.

This means, two different radio environments, e.g. cascaded scattering with no LOS component and single scattering with a LOS component and large scale fading, can yield similar aggregate statistics. Actually, any distribution can be generated by superposing scaled pdf's of different Rayleigh or Rice distributions. The crucial point is the size of the statistical ensemble, it strongly influences the outcome of the statistical analysis. Which is the correct ensemble? Again, propagation is the key for answering this question. The extent of the statistical ensemble has to be large enough to get enough independent samples but must also not exceed the corresponding stationarity region, in indoor environments sometimes an impossibility.

5. KEYHOLE PHENOMENON

The keyhole (or pinhole) phenomenon was first described by the authors of [4]. For a keyhole channel, the instantaneous channel matrix realization shows a lower rank than the averaged correlation matrices at the link ends would suggest. As an extreme case, the instantaneous channel realization is always of rank one while the correlation matrices show full rank. A corresponding channel model is provided in [5], where the 'Kronecker' MIMO channel model is adapted to keyhole channels.

A physical explanation of the keyhole phenomenon is provided by the concept of a 'narrow air pipe', where all multipath components from the transmitter merge before they, again, split up into received multipath components. Such a narrow air pipe could be formed by a small hole in a metal screen, a waveguide, or cascaded diffractions at edges. Corresponding measurements have been reported in [4, 6]. Furthermore, the authors of [5] explain that a long distance between separate Rx and Tx scattering clusters can also cause effective keyholes.

We know how a keyhole can be induced, how it can be modeled, what its effects are. However, the measurements of [4] showed only rare occurrences of weak keyholes; the authors of [6] had some troubles to artificially create a keyhole in the laboratory; and no other occurrences of keyholes have been reported yet. A waveguide or cascaded diffractions without additional multipath components seems rather unlikely, and long distances between Rx and Tx arrays are a contradiction to the high data rate requirement for MIMO systems. How relevant are keyholes to mobile communications? Is it necessary to develop signal processing or coding strategies for keyholes, or can we discard keyholes as an exotic phenomenon irrelevant to practical applications? These are important questions which can only be answered by extensive measurements and propagation studies.

6. CONCLUSIONS

In this paper, we stressed the importance of radio propagation for a thorough understanding of MIMO channels. We explained that only radio propagation can provide answers to the crucial questions of MIMO related problems. Whether assumptions like independent transmit and receive correlation, SNR dominated MIMO capacity, fading statistics that are linked to specific scenarios like LOS or NLOS, and the relevance of the keyhole phenomenon for mobile communications are true or not can only be answered by studying radio propagation and analyzing large sets of measurement data. Modeling and system design can not be done without considering the specifics of the environment where a system shall operate.

7. REFERENCES

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