Repeatable Performance Measurements of MIMO Systems in Connected Reverberation Chambers with Controlled Keyhole Effect

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Abstract. *A straightforward, fast, and repeatable procedure for measuring the system performance of the antennas in a MIMO system is presented. Due to the use of two connected reverberation chambers, the so called keyhole effect is observed and can be controlled. The method is possible to use for performance measurements of complete MIMO systems, and the present paper lays out the basics for making this possible.*

Keywords

Reverberation chamber, Multiple-Input-Multiple-Output, MIMO, antenna characterization.

1. Introduction

Multiple-Input-Multiple-Output (MIMO) technologies are becoming increasingly more popular to use in modern communication systems. MIMO systems are inherently complex and the designer of one component for such a system needs not only a rigorous investigation of the performance of the component itself, but also of all other components in the system as well as the signal environment where the system is deployed. The performance of each component will add up to the total system performance. This is especially true for the design of MIMO antenna arrays. However, since the overall goal is to maximize the total system performance it is more efficient and less time-consuming to use a method which directly measures the performance of the complete MIMO system. The reverberation chamber offers the possibility of performing such a measurement in a very short time and with high repeatability.

The reverberation chamber is a reflective enclosure, normally rectangular shaped, and equipped with so called mode stirrers to perturb the excitation of modes in the chamber. An example figure of a Bluetest reverberation chamber is shown in Fig. 1. The reverberation chamber is well known within the area of EMC (electromagnetic compatibility) testing, and has been in use for those types of measurements since the 1970's. During the last ten years, the reverberation chamber has also been established as a method for determining performance parameters for small antennas and wireless units. Bluetest in cooperation with Chalmers University of Technology have previously shown several improvements to the reverberation chamber technology, in order to make the measurements fast and accurate even in relatively small-sized chambers [1]-[3]. The reverberation chamber is now an established method for measurements of parameters like radiation efficiency [4], [5], antenna diversity gain [6]-[9], Total Radiated Power [10] and Total Isotropic Sensitivity [11]. Advantages to perform measurements of the above mentioned parameters in a reverberation chamber are the ease of use, small size, measurement speed, and cost-effectiveness.
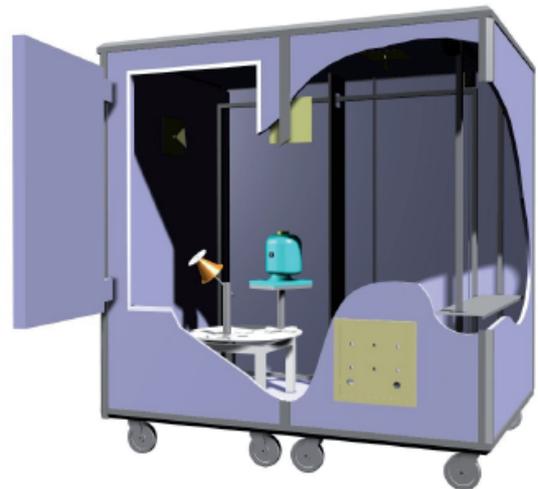
Fig. 1. Example figure of small reverberation chamber used for testing of small antennas.

The reverberation chamber supports a uniform and isotropic statistical signal environment with Rayleigh distributed signal amplitudes [12], [13], and these characteristics make it specifically useful for measurements of MIMO antenna arrays as discussed above.

Even though not within the specific scope of this paper, the reverberation chamber as a multipath emulator is very suitable for other more advanced MIMO measure-

ments, like for Multi-User MIMO (i.e. several terminals in the same system) or tests of scheduling software. A discussion of these types of measurements in the reverberation chamber can be found in [14].

Separate measurements of the performance of a single MIMO antenna array have been shown previously by Kildal and Rosengren [7]. In the present procedure, the scope is expanded to a complete MIMO system, i.e. both transmitting and receiving antenna arrays. Testing of complete active MIMO systems was demonstrated already in [15], using a single reverberation chamber. However, a single reverberation chamber provided a relatively high transmission level between the transmit and receive sides. Therefore, the tests could only be carried out for large signal-to-noise-ratios (SNR). In the present paper, we introduce the use of two connected reverberation chambers which provide the possibility to add attenuators to the coaxial cables connecting the two chambers. Thereby, we can control the effective SNR needed for a specific test, and at the same time we can keep both the transmit and receive sides in a rich and isotropic multipath environment. The results presented in this paper will enable active measurements of fully working MIMO systems in reverberation chambers.
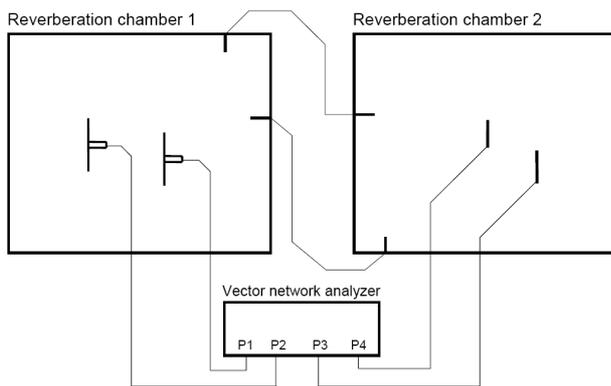
Fig. 2. Setup with connected reverberation chamber for testing of MIMO antenna arrays.

The so called keyhole effect [16] in MIMO communication systems is known as a situation where the rank of the wireless communication channel is limited, even though there is rich scattering both at the transmit and receive antenna sites. The available MIMO capacity in such a channel would be severely reduced not due to increased correlation between antenna branches, but due to the reduced rank of the channel. The perfect keyhole channel has only one mode of propagation between the transmit and receive sites, but in reality such a case would be rarely found. Instead, the case of a multi-keyhole channel would be more realistic, i.e. a case which have several modes of transmission between the two local environments surrounding the transmit and receive antenna sites, respectively. Reverberation chambers are ideally suited to simulate keyhole channels due to the very rich scattering inside the chamber, and the possibility to connect two reverberation chambers with various numbers of coaxial cables to resemble multi-keyhole channels.

2. Measurement Setup and Procedure

The measurement setup used in this investigation consists of two reverberation chambers, with the transmit antenna configuration located in one and the receive antenna configuration in the other chamber. Each chamber is equipped with a number of wall mounted monopole type antennas, and each of these fixed wall antennas are interconnected via a coaxial cable with a corresponding fixed wall antenna in the other chamber. The number of connections between the two chambers are varied in order to control the statistical richness of the channel, i.e. the rank of the channel, between the transmit and receive antenna configurations. Each element of the transmit and receive antenna configurations are connected to a separate port of a network analyzer, which facilitates fast sampling of all combinations of transmissions. Fig. 2 shows schematically the measurement setup for a 2-by-2 MIMO system in a configuration with two connections between the reverberation chambers. Photos of the chambers used in the measurements can be seen in Fig. 3 and 4.

The concept of using two reverberation chambers is very useful, because it will, via the coaxial connections, give access to the channel and give possibility to add attenuators, amplifiers, delay lines etc. to effectively change propagation conditions.

Fig. 3. Photo of one of the two types of reverberation chambers used in the measurements. This chamber with approximate inner dimensions 1.2 m-1.75 m-1.85 m.

During measurement, the transmission between each of the transmit antenna elements and each of the receive antenna elements are sampled with the network analyzer in terms of S-parameters. In the case displayed in Fig. 1, two transmit and two receive antenna elements were used, and therefore four different S-parameters were measured in each sampling point. The sampling process is repeated for a large number of combinations of mode-stirrer positions. In the present case 301 sampling points were used, which means that there were 301 different channel realizations created and sampled during the measurement.

Also an extended variation of the measurement setup displayed in Fig. 1 was analyzed. This extended setup con-

sisted of up to six connections in between the two reverberation chambers. A schematic setup is shown in Fig. 5.

Fig. 4. Photo of the second type of reverberation chamber used in the measurements. This chamber with approximate inner dimensions 0.8 m-1.0 m-1.6 m.
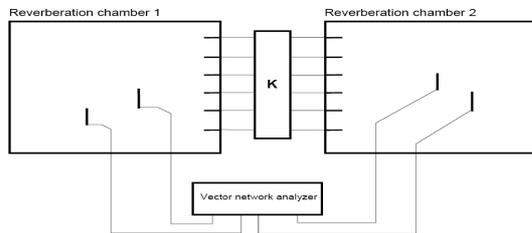
Fig. 5. Extended setup with connected reverberation chamber for testing of MIMO antenna arrays.

3. Single and Dual Connections

3.1 Test Case

To demonstrate the keyhole effect, cases with one or two connections between the chambers were tested. In addition, measurements were also performed in a single chamber, with both transmit and receive arrays placed in this same single chamber, which gives no constraint to the statistical richness of the signal environment, i.e. no keyhole effect is present.

The antennas used in the present tests were for the transmit side two dipoles, tuned to the measurement frequency of 2450 MHz. For the receive side, two monopole antennas from a commercially available WLAN router were used. Both the transmit and receive antenna arrays were configured with the elements vertically positioned and with an approximate element spacing of 10 cm. A four-port network analyzer was used to be able to measure transmissions between the antennas simultaneously.

During measurement, the mode stirrers were moved in a continuous mode, with the sampling made on-the-fly, which facilitated as short measurement time as 60 seconds. During the 60 second sequence, 301 sampling points were taken.

All measurements were performed at a frequency 2450 MHz.

3.2 Capacity Calculations

To calculate a final performance parameter, the maximum capacity measure is chosen, similar to what was done in [7]. To start with, the channel realization in each mode stirrer position (sampling point) is characterized by combining the measured S-parameters into a corresponding **H**-matrix

$$\mathbf{H}(i) = \begin{bmatrix} S_{31}(i) & S_{32}(i) \\ S_{41}(i) & S_{42}(i) \end{bmatrix} \tag{1}$$

where i is the index of the mode stirrer position, and Sxy indicates the S-parameter as measured by the network analyzer between ports x and y, where ports 1 and 2 are connected to transmit antenna elements, and ports 3 and 4 to receive antenna elements. The maximum instantaneous MIMO capacity for channel realization i can then be given by the known equation

$$C(i) = \log_2 \left(\det \left(\mathbf{I} + \frac{\rho}{2} \mathbf{H}(i)\mathbf{H}(i)^* \right) \right) \tag{2}$$

where **I** is an identity matrix of size 2-by-2 and ρ is the chosen signal-to-noise ratio (SNR). Note the division by 2, which corresponds to the use of two transmit antennas. As the final performance criteria the average maximum capacity over all channel realizations is calculated as a function of different SNR values.

3.3 Results

Fig. 6 shows a comparison of measured capacity results as a function of SNR for the 2-by-2 MIMO system.
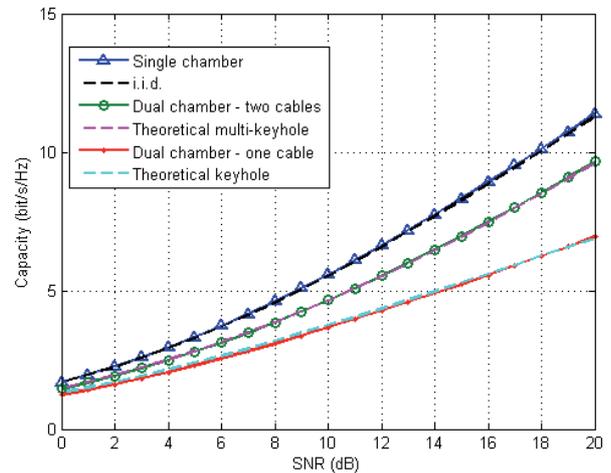
Fig. 6. Calculated MIMO capacities from measured S-parameters in reverberation chamber.

Together with the results for one and two connections between the chambers, capacity results achieved with both antenna arrays in the same chamber as well as the theoretically expected maximum capacity are shown. The theoretically expected capacities are calculated from randomized channels with complex Gaussian distribution. The i.i.d. (independent and identically distributed) case are calculated from a single complex Gaussian distributed channel,

whereas the two keyhole cases are calculated from two independent complex Gaussian distributed channels. In the latter case the total channel matrix is achieved by combining the transmit and receive environment matrices with a transfer matrix describing the transmission between the two independently distributed environments. The transfer matrix is chosen with rank 1 to simulate a perfect keyhole and with higher rank to simulate a so called multi-keyhole. In this case a rank-2 matrix was used for the multi-keyhole case, which means two independent connections between the transmit and receive environments.

The close agreement between the single chamber case and the i.i.d. case shows that the single chamber gives a very rich scattering with a full rank channel.

For the two cases with two connected chambers, the measured capacities are lower than in the single chamber case, and the cause for this is the so called keyhole effect. In fact, the case with a single cable connecting the two chambers shows a very good agreement with the perfect keyhole. The limited number of connections between the chambers will effectively limit the rank of the channel, even though each antenna array is placed in a rich scattering environment. In other words, the rich scattering in each chamber is not transferred to the other chamber. An analogy from a real world scenario could be a room or house where the modes of transmission into the building are very limited. Although it is very rare to find a single mode of transmission, like the perfect keyhole, in real world scenarios, the analysis can be extended to several simultaneous but independent keyholes. This is called multi-keyhole, and fits to the presented case with two connections between the chambers.
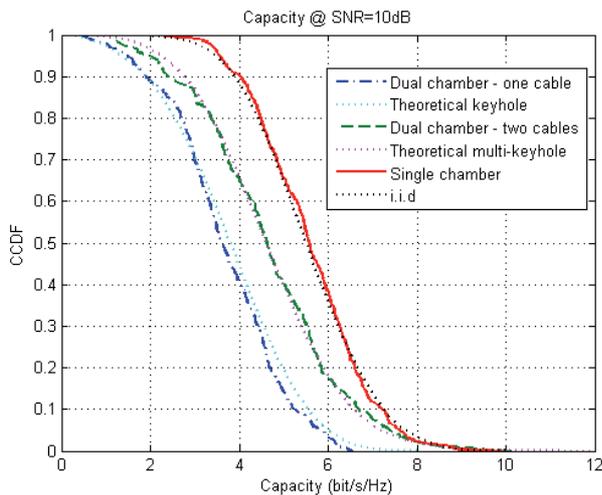
Fig. 7. Complementary cumulative distributions of measured and expected capacities, calculated for a SNR of 10dB.

For the case with two connections between the chambers we can see the agreement between measured and expected capacities for a multi-keyhole. This means that the case with two connections effectively emulates a scenario with two independent keyholes, or a multi-keyhole scenario. It is expected that more connections between the chambers will follow this trend and thereby enable the possibility of controlling the (multi-)keyhole effect in an effective manner.

Fig. 7 shows the distributions of measured capacities for SNR of 10 dB. Shown are also theoretical capacity distributions achieved from the numerical simulations described above. The agreement between measured and expected values gives more confidence to the conclusion that the reverberation chamber can be used in the proposed way for simulating different propagation scenarios for MIMO systems.

It is interesting to note that two connections between the chambers are not enough to gain full rank of the channel for a 2-by-2 system. This indicates that if the keyhole effect is present in a wireless communication system, there is a need for more propagation lines or modes than the target rank of the MIMO system, in order to fully combat the keyhole effect. For the measurement procedure presented in this paper, the result shows that the keyhole effect can actually be controlled by using different number of connections between the two reverberation chambers. Although the results presented here are based on measurements of passive MIMO antenna arrays, the future usefulness of the method presented here will be for active MIMO measurements, where the full MIMO system, including both antenna and circuitry on both transmit and receive side, is tested. The extension of the procedure to active tests is straightforward.

4. More Than Two Connections

In the previous case with one and two connections between the chambers, the keyhole effect was explored. In this case more connections are added between the chambers in order to increase the rank of the created MIMO channel.

4.1 Test Case

A similar test case as the one described above was used also in this case, with the biggest difference being that six fixed measurement antennas were placed in each chamber, and then connected together with six coaxial cables. A schematic setup is shown in Fig. 5. As can be seen in the figure, there is a connection matrix $\mathbf{K}$ determining the actual connection for each line. This is shown to display the possibilities of introducing for instance attenuation, amplification, phase shift or time delay on each line connecting the chambers. The total channel matrix can then be described with the following equation

$$\mathbf{H}_{tot} = \mathbf{H}_1 * \mathbf{K} * \mathbf{H}_2 \qquad (3)$$

where $\mathbf{H}_1$ is the H-matrix measured in the first chamber, $\mathbf{H}_2$ the H-matrix from the second chamber, and $\mathbf{K}$ is a diagonal matrix with as many non-zero entries as there are connections between the chambers.

For characterization of the measurement setup it is obvious from (3) that the channel matrix for each of the

two chambers can be measured separately, and then be combined by using a virtual connection matrix **K** to give the total channel matrix. This is how the tests presented in this section were performed, which gave the added value of being able to test with any combination of values in the **K** matrix by using post processing calculations of the measured data. Fig. 8 shows the somewhat modified setup to measure the channel matrices of the two chambers separately.
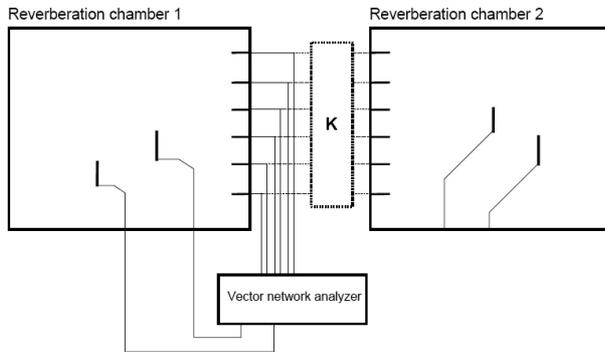
Fig. 8. Setup used for characterization of dual chamber setup with up to six connections in between the two reverberation chambers.

4.2 Results

Fig. 9 shows results from capacity calculations with data from the extended measurement setup with up to six connections.
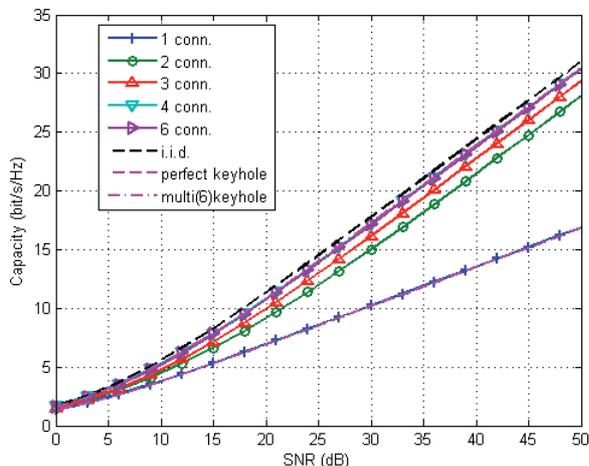
Fig. 9. Measured and calculated capacities for a MIMO system in two reverberation chambers with up to six connections.

The cases with one and two connections are equal to what was measured in the original measurement setup described previously, also here showing an agreement with the perfect keyhole channel for the single connection case. For more connections we can see that the capacity is asymptotically increasing towards the ideal i.i.d. channel case. Due to the statistical nature of the data, we can hardly distinguish between the cases of four and six connections, and these two are also close to the i.i.d. case. Empirically, we can then draw the conclusion that for a practical measurement case with the presented setup, four connections between the two chambers are enough to give a close to ideal channel performance. It should be noted that this is valid for a 2-by-2 MIMO system. For systems with higher complexity more connections are probably needed.

5. Conclusions

A procedure for system performance testing of MIMO antenna arrays is presented, and the results show the validity and usefulness of the procedure. The procedure is utilizing two reverberation chambers, connected with coaxial transmission lines, and therefore gives the opportunity to introduce the keyhole effect into MIMO measurements, as well as controlling the amplitude and phase of the MIMO channels. Adding more connections between the chambers increases the rank of the created channel, and for a 2-by-2 MIMO system four connections is enough with the tested measurement setup to get similar capacity values as in an ideal, full-rank channel.

Acknowledgements

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