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***Abstract*—We utilize two reverberation chambers (RC) to characterize two four-port antennas. The RC set-ups contain four mounted fixed antennas. This configuration allows to sequentially measure the full 4x4 MIMO capacity of the AUT with only a two port VNA without any alterations of the configuration inside the chamber between measurements. The results show that an RC is a powerful tool to characterize complex multi-element antennas that can easily be extended with more ports when this is required. The two RCs main difference is in the size, with a large chamber designed to fit large test objects and a smaller model designed for mobile devices. We show that there is high repeatability between measurements in the different chambers, indicating the stability of the RC technique.**

***Index Terms*—MIMO capacity, reverberation chamber, eleven antenna, 4x4**

I. Introduction

New communication standards such as LTE Advanced and IEEE 802.11n define high speed communication modes consisting of large numbers of transmit and receive antennas to utilize multiple-input multiple-output (MIMO) communication. Traditionally, antenna measurements have been performed in anechoic chambers, consisting of an antenna under test-holder (AUT-holder) capable of rotating the device in the azimuthal and elevation planes, absorbing walls and a fixed-antenna for measuring the radiation pattern. These test-facilities are now being complemented with multiple fixed antennas in specific geometric constellations and channel emulators to be able to measure advanced MIMO devices and emulate rich scattering environments. Increasing the number of antennas results in a vastly more complicated measurement configuration, and increased measurement cost and time.

Another method for measuring MIMO capacity is to utilize a reverberation chamber (RC), which is the opposite of an anechoic chamber [1]. An RC consists of a metal cavity with highly reflective walls and one or several methods for switching between the modes in the chamber (known as stirring) [2]. The fields inside the RC are Rayleigh distributed in time (on the time scale of the stirring speed) and space (on the length scale of the wavelength), emulating a rich isotropic multi-path environment. The RC method for measuring antenna parameters has the benefits that it is fast, cost effective and easy to implement and operate. RCs have previously been used in several works to investigate MIMO properties of active and passive devices, see e.g. [3], [4]. In this paper, we show that the RC method can effectively be used to measure the performance of complicated multi-element antennas.

We present results of RC measurements on the Eleven antenna used in a four-port MIMO configuration. We choose this antenna since it is already characterized in two and three port configurations. See [5]–[7] and references therein for information on the Eleven antenna and earlier measurements on it. It is also an antenna with a known low correlation between the ports and it operates at high frequencies, providing a performance test case for the RC methodology. The Eleven antenna is an 8-port log-periodic dual-dipole array antenna. In this paper we report the results from measurements on one of the ports in each dipole branch, see figure 1a, with the other port left open. We also measure the MIMO capacity on two CTIA MOSG reference antennas [8] operating at $\sim 700-800$ MHz. These antennas are two-port PIFA antennas fabricated for testing MIMO measurement set-ups. Here we have used a fixture based on Rohacell for separating the two antennas and fixing them during measurements, see figure 1b. The spacing between the MOSG antennas is 65 mm.

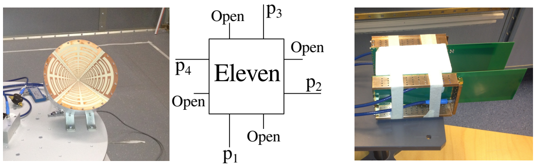
In an RC, the mode stirring provides a means to create a Rayleigh fading environment. Thus, we measure the MIMO capacity in a Rayleigh fading environment for a set-up with equal number, $N = 4$, of transmit and receive antennas. We consider the case when the sender has no channel state information (CSI) and the receiver has perfect CSI, resulting in a capacity [9]

$$C_N = \mathbb{E}[\log_2 \det(I_N + \frac{\rho}{N} H H^\dagger)], \tag{1}$$

where $\mathbb{E}[\cdot]$ denote the expectation value, ρ is the SNR, I_N the $N \times N$ identity matrix, $(\cdot)^\dagger$ denotes Hermitian conjugate and H the channel matrix. The channel matrix include effects from send- and receive antennas as well as from the RC environment.

II. Measurement set-up and method

In this work, two chambers were used. A Bluetest RTS90 RC equipped with a 4-port fixed antenna and a 4-port switch box for switching between the 4 ports. The modes are stirred using 5 stirrer plates and a turntable. The second system was a Bluetest RTS60 RC with the same fixed antenna, switch box and turntable configuration as the RTS90. There are however only two stirrer plates in the RTS60 system. The turntable is equipped with four ports, making it possible to connect



(a) (b)

Fig. 1. (a) Photo of the Eleven antenna mounted on the turntable in the RC and the four-port configuration of the Eleven antenna used in this paper and (b) photo of the MOSG antennas configuration with Rohacell fixture used as a 4-port MIMO antenna and placed on a PVC table as used inside the RC.

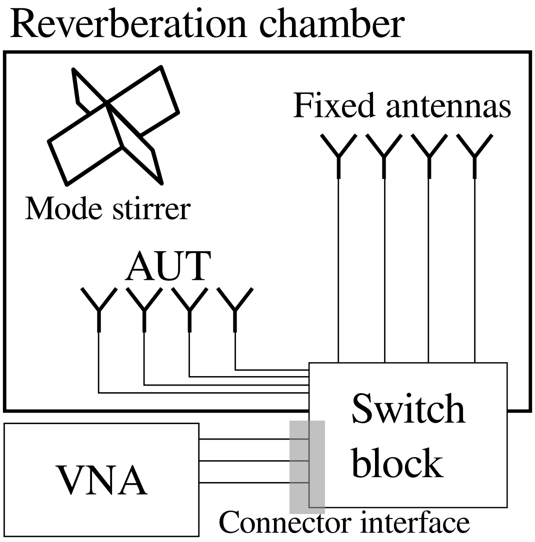


Fig. 2. Measurement set-up.

all four ports of the Eleven antenna before the measurement starts. During the measurement, no modifications to the set-up was made inside the chamber, eliminating measurement errors introduced by reconnecting the four antenna ports between the measurements. The main difference between the RTS60 and RTS90 is the chamber size where the RTS60 has inner dimensions 1.2 m×1.7 m×1.8 m while the RTS90 has inner dimensions 3.3 m×4.2 m×2.5 m. The set-up is depicted in figure 2 and covers both the RTS60 and RTS90.

We chose to characterize the Eleven antenna at the frequencies $f = 3800 - 5600$ MHz. This span was reported earlier in [5]. The MOSG antennas were characterized in the interval $f = 730 - 780$ MHz since this is its designed operating frequency span.

A. Correlation measurements in a reverberation chamber

S-parameters can be used to compute the Pearson correlation coefficient between two antenna elements. It is defined as

$$\rho_{X,Y} = \frac{\mathrm{cov}(X,Y)}{\sigma_X \sigma_Y},$$

where $\mathrm{cov}(X,Y)$ denote the covariance and can be estimated as

$$\mathrm{cov}(X,Y) = \sum_{i=1}^{N}(X_i - \bar{X})(Y_i - \bar{Y}),$$

where $\bar{X}$ denote sample average and

$$\sigma_X = \sqrt{\sum_{i=1}^{N}(X_i - \bar{X})^2}$$

is the standard deviation estimate. If X and Y are represented by measured S-parameters, these equations can be used to compute the correlation between two antenna elements in an RC. This is used in the computations below.

B. Measurement procedure

The measurement was initiated by a reference measurement (measuring S_{12}) performed using a known calibration antenna to assess the overall loss in the chamber. In this measurement, the mode stirrers were moved continuously to provide an average loss in the RC for all mode stirrer positions. Next, the AUT was connected to the set-up. The VNA port A was connected to the switch box which provide switching between the four fixed antenna elements. VNA ports B and C were connected to ports 1 and 2 of the AUT and S_{12} and S_{13} were measured for the selected frequency span. The measurement was performed in a stepped mode stirrer sequence where the mode stirrers were set to a fixed position for each measurement of S_{12} and S_{13}. When all stirrer positions (200) were measured, the VNA ports B and C were connected to ports 3 and 4 of the antenna by moving connectors outside of the chamber at the connector interface, see figure 2, and the measurement sequence was repeated. The elements not connected to the VNA were terminated outside of the RC using 50Ω-loads.

The procedure described above is required since the VNA only has four ports and thus all four ports of the AUT can not be measured simultaneously. This makes repeatable positioning of the stirrers an important matter, so that stirrer configuration 1 in measurement sequence 1 is exactly the same as stirrer configuration 1 in measurement sequence 2 and so on. This is verified by performing a repeated measurement on the same antenna element in two mode stirrer sequences. The correlation is then required to be close to 1. This was indeed also found, and can be seen in figure 5b. Note that the correlation is close to 1 for all frequencies, indicating high resolution repeatability of the mode stirrer plates. If there is any difference in positioning, this will result in a decrease in correlation. If this happens, a MIMO capacity measurement will over-estimate the antenna capacity since then the different antenna elements in the two sequences will appear to be lower correlated than they actually are.

III. Results

Results from computing the MIMO capacity at $\rho = 10$ dB using equation 1 are plotted in figure 3 for the Eleven antenna and in figure 4 for the MOSG antennas. For the Eleven-antenna, note that the capacity when used as a two port antenna is very similar for the case when two parallel ports and two perpendicular ports are used.

Figure 5a depict the eigenvalue distribution of H when measured in the RTS60 and using the Eleven antenna. Figure 5b

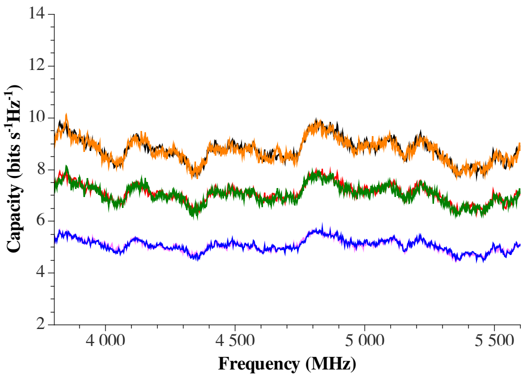


Fig. 3. MIMO capacity of the Eleven-antenna for $\rho = 10$ dB measured in RTS90 when using four (black), three (red) and two (blue and purple) ports and in RTS60 when using four (orange) and three (green) ports respectively. The two-port configurations are for perpendicular (purple) and parallel (blue) antenna elements.

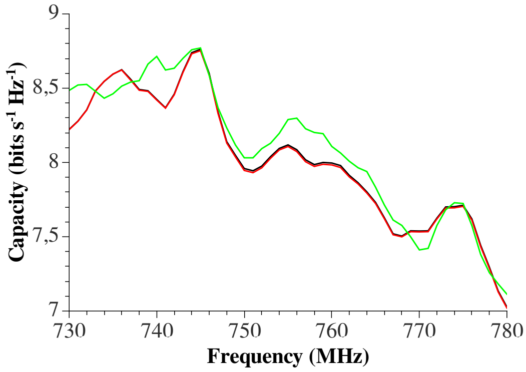


Fig. 4. MIMO capacity of the MOSG antennas for $\rho = 10$ dB measured in RTS60 three times. Red and black show repeated measurements without any modification in the chamber. Green depicts the same measurement but when the antenna was repositioned in the chamber to indicate difference between measurements. Note that the black curve is difficult to see since it is almost completely overlapped by the red curve.

shows the correlation of a single element when measured two times sequentially in a stepped procedure. That is, S_{12} is measured for all 200 stirrer positions in a sequence, and stored and then the same stirrer position sequence is repeated and the 200 S_{12} parameters are measured again.

IV. Discussion

We have measured the MIMO capacity of the Eleven antenna and the MOSG antennas using two four-port equipped reverberation chambers. The fact that the chambers are equipped with four ports and RF switching capabilities between the ports give the possibility to investigate four-port antennas without any reconfiguration inside the chamber. This eliminates errors introduced by switching cables between measurements. Repeated measurements on the Eleven antenna inside two RCs as well as repeated measurements on the CTIA MOSG reference antennas were presented.

The high resolutions repeatability of the mode stirrer plates indicated by the high correlation seen in figure 5b shows that

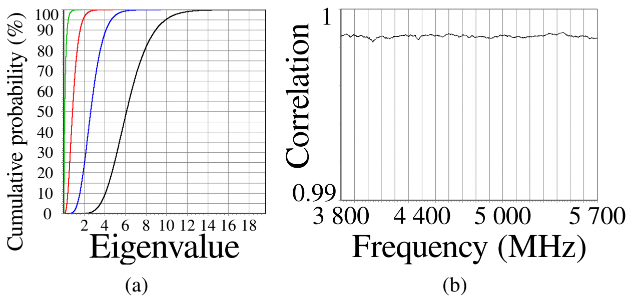


Fig. 5. (a) Eigenvalues of H for the Eleven antenna when places in the RTS60 sorted in order of size. (b) Absolute value of Pearson correlation between the same antenna element measured in a stepped measurement procedure two times. Note the vertical axis scale ranging from 0.99 to 1.

the RC can be used to measure MIMO quantities also at high frequencies. Thus the RC system can be used to measure e.g. throughput of a 802.11n MIMO devices operating in the 5 GHz band or for design of antenna systems operating in this range.

In figure 5a the eigenvalues of the channel matrix is plotted. All four eigenvalues are of the same order, indicating the full rank of the channel matrix H, which is the definition of a rich scattering environment [10]. This is an important property of the test system to fully characterize the MIMO capacity of the AUT. If the channel matrix is not full rank, the capacity will be underestimated.

It was shown in figure 3 that the difference between the two RC systems when measuring is very small, indicating the stability of the RC methodology for assessing MIMO capacity of an antenna. It is noted that it is important to operate the mode stirrers in a way that provide this high positioning repeatability rate, e.g. by using stepper motors operated using micro-stepping.

The MOSG antennas were measured repeated times in the smaller RTS60 chamber with high repeatability, indicating that the system can be used also at low frequencies for assessing the MIMO capacity. If measurements on active MIMO devices are performed these often operate at lower frequencies. It was found that the RTS60 system provides good repeatability also for AUTs operating at 700 MHz.

The capacity of the MOSG antennas is somewhat lower than the Eleven-antenna. This is due to the fact that there is a higher correlation between the antenna elements in the MOSG antennas than in the Eleven antenna and lower average efficiency on the elements.

V. Conclusion

We conclude that the RC methodology is a stable and efficient method of measuring MIMO properties of antennas and active devices. It it important to have an efficient stirring mechanism to create a rich scattering environment and high precision positioning of the stirrers for repeatable results. Measurement results are not sensitive to the RC as such, and different chambers give the same measured result given the above criteria.

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