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Passive characterization of the couplings within a multi-antenna system through noise correlation

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Abstract— This communication deals with a technique to passively retrieve the couplings between several antennas. The mutual-impedance of coupled antennas are deduced from field correlations in a reverberation chamber (RC). It is experimentally shown that the impedance matrix between 2 slot antennas or 3 horn antennas are reconstructed with good accuracy whatever the antenna properties. The accuracy is quantified with respect to the distance between the antennas.

Keywords— Multi-antenna system, reverberation chamber, measurements, antenna coupling, noise-correlation.

I. INTRODUCTION

The increasing demand for higher transmission rates and quality of service in existing and emerging wireless communication systems requires solutions to improve their performance. One solution is the use Multiple Input Multiple Output (MIMO) methods [1], [2]. This last uses multiple transmit and receive antennas to ensure reliable connections and good network coverage without increasing the transmit power or spectral bandwidth. However, the improvements of multi-antenna systems are accompanied by significant technical challenges. These multiple antennas suffer from high correlation and mutual coupling [3]. As it has been demonstrated that mutual coupling can have a positive or negative effect, its evaluation remains an essential tool for estimating the performances of the MIMO system [4]. Hence, taking mutual coupling into account in multi-antenna systems, either in their design or in antenna processing algorithms, allows improve the actual radiation efficiency of each element.

In this context, this article aims at validating a novel technique to passively characterize the coupling between the elements of a multi-antenna system by diffuse field correlation in a reverberation cavity.

Based on an analogy with results obtained in acoustics and seismology [6], [7], we showed experimentally that the cross-spectral density between mutual-impedances is linearly related to the radiation impedance between two receiving antennas [8]. Very recently, the underlying theory was derived [9] and it provides the expression of the cross-spectral density with respect to the real part of the impedance between two antennas in a reverberation chamber. This expression takes into account both the cavity losses and the antenna efficiency, which were not considered in previous works on correlation of S-parameters that only focused on lossless antennas [10].

This paper presents a validation and an extension of the aforementioned passive method. In Section II, we extend

the theoretical developments between the Power Spectral Density (PSD)/the Cross Spectral Density (CSD) and the real part of the self/mutual-impedance to N coupled antennas. These theoretical formulas are validated in Section III using two facing slot antennas as receiving antennas. In Section IV, we test the robustness of our method by varying the distance between the antennas under test (AUT) and evaluate the convergence of the passive reconstruction to the active reference measurement by computing the Pearson similarity coefficient. Section V is dedicated to the application of the impedance correlation technique to estimate the coupling between each pair of antennas in a system consisting of three elements. After discussing the measurement results, we conclude this paper.

II. THEORY

We consider a Tx-antenna of self-impedance Z_{TxTx} and of radiation efficiency η_{Tx} . A set of N coupled Rx-antennas is characterized by its impedance matrix. One element of this matrix Z_{ij} is the mutual-impedance between antenna i and j when $i \neq j$ and the self-impedance of antenna i when $i = j$. An example of 2 antennas A_1 and A_2 placed in a reverberation chamber (RC) of volume V is illustrated in Fig. 1. We assume that the load impedance of each Rx-antenna is sufficiently high such that the voltage induced on Rx-antenna i by the Tx-antenna is directly proportional to the mutual-impedance Z_{iT_x} . The auto and cross-correlations, i.e., the cross and power spectral densities between Z_{iT_x} and Z_{jT_x} are defined as

$$\mathbf{C}_{ij} = \langle Z_{iT_x} Z_{jT_x}^* \rangle. \quad (1)$$

Symbol $\langle \cdot \rangle$ indicates an averaging over all measurement configurations in the RC.

Based on the theory developed in [9], the impedance correlation can be expressed in terms of the average energy density W as follows:

$$\mathbf{C}_{ij} = \frac{c \langle W \rangle \lambda^2}{2\pi |I_{T_x}|^2} \Re(Z_{ij}). \quad (2)$$

If a source antenna transmits a power P_{T_x} expressed by Eq.3, all of this power is absorbed through dissipation processes in the RC.

$$P_{T_x} = \eta_{T_x} \Re(Z_{T_x}) |I_{T_x}|^2. \quad (3)$$

The transmitted power in this case is given by :

$$\langle P_{Tx} \rangle = \langle W \rangle V \alpha \quad (4)$$

From equations 3 and 4, we can extract the expression of W , which will be substituted into the impedance correlation expression, resulting in the following expression of impedance cross-correlation $C_{Z_{i \neq j}} = \langle Z_{iTx} Z_{jTx}^* \rangle$,

$$C_{Z_{i \neq j}} = \frac{\lambda^2 c \eta_{Tx} \Re(Z_{TxTx})}{2\pi \alpha V} \Re(Z_{ij}) \quad (5)$$

as well as the autocorrelation expression $C_{Z_{ii}} = \langle Z_{iTx} Z_{iTx}^* \rangle$,

$$C_{Z_{ii}} = \frac{\lambda^2 c \eta_{Tx} \eta_i \Re(Z_{TxTx})}{2\pi \alpha V} \Re(Z_{ii}), \quad (6)$$

where λ is the wavelength, α the RC energy decay rate, and $\eta_i = R_i / \Re(Z_{ii})$ is the radiation efficiency of antenna i (R_i is the radiation impedance).

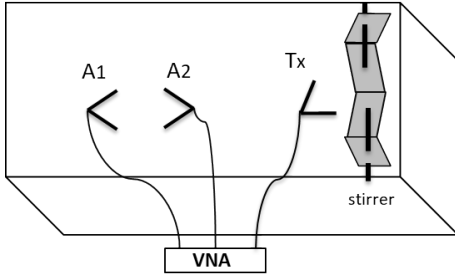


Fig. 1. Measurement configuration in a reverberation chamber with a source antenna T_x and two antennas under test A_1 and A_2 .

III. EXPERIMENTAL RESULTS

A. Measurement Setup

All experiments are performed within the ESYCOM RC of dimensions $2.95 \times 2.75 \times 2.35$ m³ whose lowest usable frequency is estimated to be 400 MHz. It is equipped with a Z-fold mechanical stirrer (60 equally-spaced positions are considered over a full rotation). The source antenna, labelled “ T_x ”, is a horn antenna oriented towards the mechanical stirrer and positioned on a vertically-rotating structure in order to perform source stirring over $N_{src} = 11$ positions.

a- Experiment with 2 receiving antennas

For the first experiment, two antennas under test (AUTs), labelled “ A_1 ” and “ A_2 ” are facing each other, separated by distance $d = 30$ cm. A_1 and A_2 are slot antennas, based on a half-disc slot excited by a microstrip with a frequency bandwidth from 1.7 to 2.8 GHz (Fig. 2). Scattering parameter measurements are carried out at 9001 frequency samples uniformly spaced on the frequency band of [1.4 - 3.2] GHz with a Rohde & Schwarz ZNB20 Vector Network Analyser (VNA).

To investigate the convergence of the estimated impedances to the measured ones, we analyze the impact of the distance between the AUTs. Specifically, we keep antenna A_1 fixed and move antenna A_2 to vary the distance between the two antennas from 30 cm to 50 cm, with a step of 10 cm.

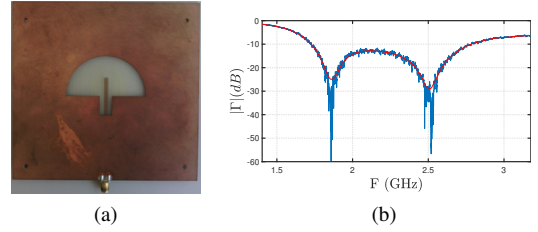


Fig. 2. (a) Photo of the slot antenna; (b) reflection coefficient

b- Experiment with 3 receiving antennas

The second experiment consists of an extension of the proposed method to the case of 3 antennas in reception. For this purpose, we examine a reception system of three directional horn antennas. Two of the antennas, A_1 and A_2 , are SH800 model horn antennas. The third antenna, A_3 , is a Schwarzbeck horn antenna. These antennas are arranged facing each other and are separated by distances of $d_{12} = 36$ cm, $d_{13} = 35$ cm and $d_{23} = 28$ cm and the measurement is performed in the frequency range [1-5] GHz.

We perform the mutual-impedance reconstruction for each pair of receivers using the impedance correlation between the source antenna and each receiving antenna individually.

B. Data Processing

As we are only interested in the Z-parameters, the measurements of the scattering parameters between the source antenna and each AUT are carried out using the same loading conditions as if the impedance were directly measured, i.e. by loading the other two AUTs by an open circuit. The obtained S-sub-matrix permits to extract the Z-matrix between the T_x antenna and the AUT. This operation is repeated for each AUT. A further reference measurement was conducted by utilizing all the ports of the VNA. This enabled a comparison between the results obtained through correlation method and those acquired from a direct measurement for both mutual and self-impedances.

C. Results

a- Results with 2 AUTs

Figs. 3, 4 and 5 show the results of the real parts of the mutual-impedance Z_{12} as well as the self-impedances Z_{11} and Z_{22} reconstructed passively by the impedance correlation method compared to those obtained by active measurements, for the first experiment, in both the frequency domain and the time domain through inverse Fourier transform. A good agreement is observed between the impedance values obtained from the correlation method proposed and the ones measured directly between AUTs.

In Fig. 6a, the time of arrival of the main peak is plotted as a function of the spacing between the AUTs, resulting in a straight line with a constant slope. As expected, the displacement of the peak position between two consecutive measurements corresponds to a distance variation of 10 cm. We observe in Fig. 6b that the amplitude of the peak decreases as the distance between the antenna increases.

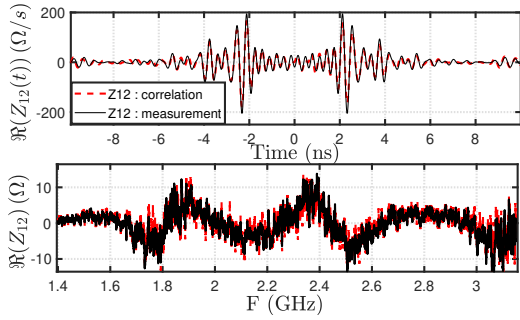


Fig. 3. The real part of Z_{12} obtained by a direct measurement between 2 slot antennas or through cross-correlation between impedances Z_{1Tx} and Z_{2Tx} for a distance of 30 cm between AUTs, as a function of time (above) and frequency (below).

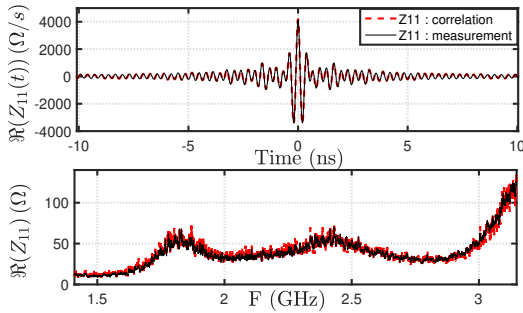


Fig. 4. The real part of Z_{11} obtained by a direct measurement between 2 slot antennas or through auto-correlation of impedance Z_{1Tx} , for a distance of 30 cm between AUTs, as a function of time (above) and frequency (below).

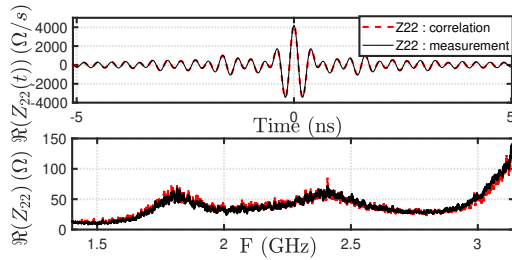


Fig. 5. The real part of Z_{22} obtained by a direct measurement between 2 slot antennas or through auto-correlation of impedance Z_{2Tx} , for a distance of 30 cm between AUTs, as a function of time (above) and frequency (below).

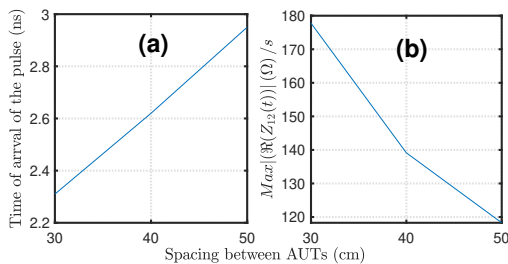


Fig. 6. (a) The variation of the arrival time of the pulse related to the direct path as a function of the spacing between AUTs; (b) The variation of the amplitude of the pulse related to the direct path as a function of the spacing between AUTs

The results of the reconstruction of the self-impedances Z_{11} and Z_{22} for the three different spacings between the AUTs are depicted in Fig. 7. It can be observed that the self-impedances of the AUTs are not affected by the spacing between them.

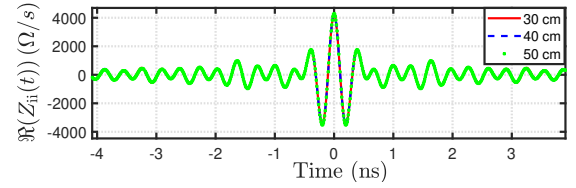


Fig. 7. The inverse Fourier transform of the real part of self-impedances obtained by the correlation method between 2 slot antennas for three different spacings between them.

To evaluate how closely the impedances estimated from the theoretical model match up with those obtained through an active measurement between antennas, we compute the Pearson similarity coefficient and the obtained results are indicated the table below.

Table 1. Pearson correlation coefficient calculated for impedances obtained by direct measurement or by the correlation method in the cases of 2 AUTs and for three different spacings.

	30 cm	40 cm	50 cm
$\Re(Z_{11})$	0.9972	0.9971	0.9971
$\Re(Z_{22})$	0.9968	0.9971	0.9968
$\Re(Z_{12})$	0.9065	0.8728	0.8538

Based on the information presented in Tab. 1, it can be concluded that the self-impedances are not significantly affected by the spacing between AUTs. However, the reconstruction of mutual-impedance becomes less precise as the distance between AUTs increases. Actually, the observed reduction in amplitude, depicted in Fig. 6b decreases the signal-to-noise ratio and therefore the Pearson correlation coefficient.

b- Results with 3 AUTs

The real parts of the mutual-impedances Z_{12} , Z_{13} and Z_{23} for the three antenna system were measured passively using the correlation method. These measurements are then compared to the results obtained by directly measuring the mutual-impedance. Figs. 8, 9, and 10 present the results in both frequency and time domains.

To assess the similarity of mutual-impedances obtained through passive measurements using impedance correlation method with those obtained through active measurements for each pair of receiving antennas, we computed the three Pearson coefficients. Tab. 2 displays the results, which yields an average Pearson coefficient of 0.75. This value is deemed acceptable as the antennas are not oriented facing to each other, leading to a weak coupling between them (and thus a reduced signal-to-noise ratio).

It is important to note that the distance between antennas is a crucial factor in achieving convergence. This is because the

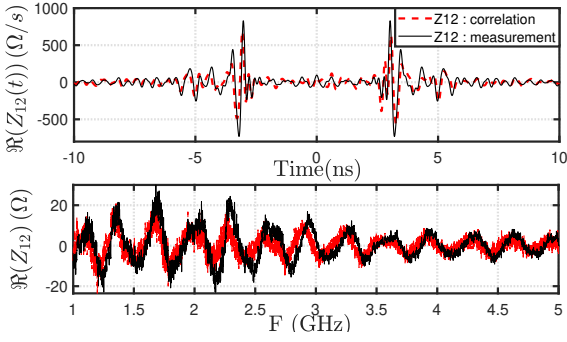


Fig. 8. Real part of Z_{12} obtained by a direct measurement between A_1 and A_2 or through cross-correlation between impedances Z_{1Tx} and Z_{2Tx} for a distance of 36 cm between AUTs, as a function of time (above) and frequency (below).

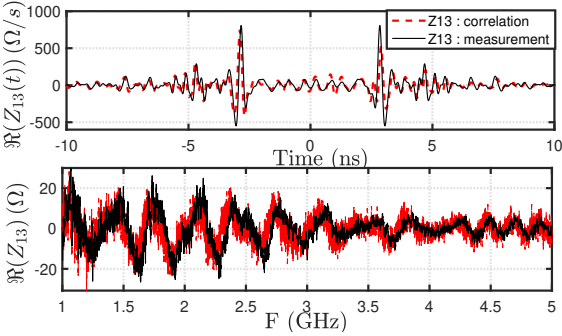


Fig. 9. Real part of Z_{13} obtained by a direct measurement between A_1 and A_3 or through cross-correlation between impedances Z_{1Tx} and Z_{3Tx} for a distance of 35 cm between AUTs, as a function of time (above) and frequency (below).

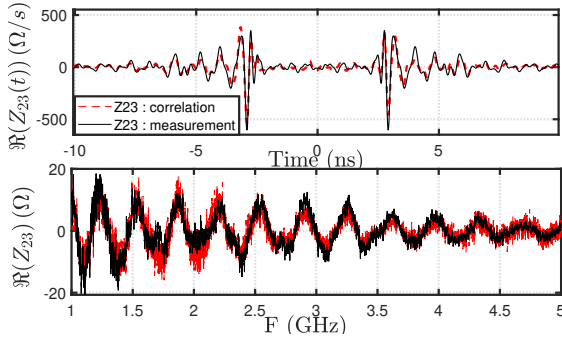


Fig. 10. Real part of Z_{23} obtained by a direct measurement between A_2 and A_3 or through cross-correlation between impedances Z_{2Tx} and Z_{3Tx} for a distance of 28 cm between AUTs, as a function of time (above) and frequency (below).

Table 2. Pearson correlation coefficient calculated for the real part of the mutual-impedance, between each antenna pair, in the case of 3 AUTs, obtained by direct measurement or by the correlation method.

$\Re(Z_{12})$	$\Re(Z_{13})$	$\Re(Z_{23})$
0.6822	0.6864	0.8979

degree of coupling between antennas rises as their distance decreases. This phenomenon is demonstrated by the highest similarity value of Z_{23} , which corresponds to the lowest spacing (28 cm) between antennas A_2 and A_3 .

IV. CONCLUSION

In this paper, a method for characterizing the coupling between antennas using correlation of the diffuse field generated in a reverberation chamber is presented. Through experimental validation, it has been shown that the mutual impedance between two slot antennas can be accurately obtained at three different distances between the AUTs. Furthermore, the method has been validated with a system comprising three AUTs, successfully retrieving the coupling between each antenna pair. This technique is not limited to a specific number of elements and can be expanded to larger arrays, allowing for faster characterization of antenna arrays.

The notable advantage of this method is that it does not require multiple measurements in both transmit and receive modes to characterize the mutual coupling between antenna pairs. Instead, all antennas in the system can remain in receive mode while a single transmit antenna is introduced to measure the entire system in a single instance. The precision of this method depends on the measurement environment, specifically the reverberation chamber used in this study. The limitations encountered in measuring within a reverberation chamber are influenced by various factors, including the number of uncorrelated configurations. However, these limitations are not inherent to the method itself but rather stem from the characteristics of the measurement environment. By ensuring improved conditions of diffuse fields, optimal precision can be achieved.

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