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The Effect of Peripheral Equipment Loading on Reverberation-Chamber Metrics

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Abstract—Measuring wireless devices in a reverberation chamber often requires ancillary equipment to be present in the chamber. This paper illustrates the effect of their presence on metrics that are important in wireless device tests, such as chamber decay time, coherence bandwidth, and antenna efficiency calculations. The results show decreases in chamber decay time of approximately 20\% when power supplies and power cords are present in the NIST chamber. For the chamber studied, the effect is approximately 10\% with a regular power cord, demonstrated to be mostly caused by the copper conductors through measurements and a model of the cord insulation. The effect on antenna efficiency by using a predetermined time constant is shown to be between 5\% and 10\% for different setups. Results from two reverberation chambers are presented, showing lower percentages for a chamber with higher losses.

Index Terms—absorption cross section (ACS), antenna efficiency, chamber decay time, coherence bandwidth (CBW), reverberation chamber (RC)

I. INTRODUCTION

A reverberation chamber (RC) is a shielded enclosure that acts as a resonant cavity. Mode stirrers, such as metal paddles, moving walls, or turntables, are placed inside the chamber to enable different modes, creating an environment which, ideally, provides the same distribution of field samples anywhere in the working volume when the fields are sampled over a stirring sequence. An RC is most commonly used for electromagnetic compatibility (EMC) measurements or for measuring performance of wireless devices, but it is also used for characterizing antenna efficiency and absorptive properties of materials [1] - [9].

When a lossy material is placed in the chamber, some of the power in the chamber is dissipated in the object, hence lowering the quality factor (Q) of the RC. Past work shows that the amount of power dissipated in the material can be determined by measuring the Q of the RC with and without the object, and, therefore, the absorbing properties of the object and the absorption cross section (ACS) [1] - [5], [8], [9].

For measuring the performance of wireless devices, it is important to set up the chamber correctly in terms of antenna placement and orientation, number of mode-stirring samples, etc [10]. Earlier work describes how to do this with and without known lossy materials such as RF absorbers present in the chamber, taking into account important metrics like spatial uniformity and chamber decay time ($\tau_{RC}$) [9] - [12]. However, peripheral equipment such as power cords or power supplies can affect the chamber setup due to their absorbing, reflecting, and potentially interfering emissions characteristics.

The chamber decay time, also referred to as the time constant, is an important metric of an RC setup that directly relates to the Q. This constant is inversely proportional to the coherence bandwidth (CBW) of the chamber, which defines the bandwidth over which frequency samples have a correlation higher than a certain threshold. To efficiently reduce measurement uncertainty, it is necessary to have as many uncorrelated samples as possible. Samples can be acquired by different stirrer positions, antenna positions and by frequency points. A long time constant indicates a well resonating RC with a low CBW, hence more uncorrelated frequency samples. However, a wider CBW is often desirable for communication signal measurements, as it reduces the frequency selectiveness. This is often required for demodulating the signal [10].

The time constant is also used for determining antenna performance characteristics like the total and radiation antenna efficiency [13]. Some antennas, such as those tunable over multiple frequency bands, require extra measurement equipment to be placed in the chamber, which, if not properly characterized, could impact the chamber characteristics and therefore result in less-accurate measurements.

Earlier work on ACS measurements describes the effect of different materials on the chamber characteristics [5], but to our knowledge, research on the effect of peripheral equipment such as power cords or power supplies, is yet to be performed. The focus of this paper lies mainly in their effects on $\tau_{RC}$, since this metric directly relates to CBW and, if predetermined, antenna efficiency. These characteristics are important when carrying out Over-The-Air (OTA) measurements in an RC. The theory behind these metrics is described in Section II, methods used for the measurement setup and a model using the ACS are presented in Section III. Section IV shows the results and illustrates the loss effect of a power cord which, if not properly accounted for, would cause errors in antenna efficiency measurements and Section V is the conclusion.

II. THEORY

A. Chamber decay time

To determine the chamber decay time, a method described in [14] was used, where $\tau_{RC}$ is determined from the power
to two-antenna method described in [13] was used because this method does not require the efficiency of the reference antenna to be known, and it only requires a single measurement. It is based on the difference in Q between the time and frequency domain, where the former does not include early-time behavior, see (2), while the latter does. Two antennas are placed in the RC and connected to a Vector Network Analyzer (VNA). Using the time constant and the extracted S-parameters from the VNA, the total antenna efficiency can be determined using

\[
\eta_{AUT}^{\text{tot}} = \frac{8\pi f^2}{c^3 \tau_{RC}} \frac{|S_{21} - \langle S_{21} \rangle_N|^2}{\langle |S_{11} - \langle S_{11} \rangle_N|^2 \rangle},
\]

where \( V \) is the volume of the chamber [m³] and \( c \) the speed of light [m/s]. \( |S_{21} - \langle S_{21} \rangle_N|^2 \) is the stirred energy component of \( S_{21} \). To determine the radiation efficiency, a correction for antenna mismatch is added to (3), given by

\[
\eta_{AUT}^{\text{rad}} = \frac{\eta_{AUT}^{\text{tot}}}{1 - |\langle S_{11} \rangle_N|^2}.
\]

The total and radiation efficiency \( \eta_{AUT}^{\text{tot}} \) and \( \eta_{AUT}^{\text{rad}} \) of the reference antenna can be determined in a similar way by replacing \( S_{11} \) with \( S_{22} \) and vice versa, and \( S_{21} \) with \( S_{12} \), in (3) and (4).

### III. Experiment Design and Model

#### A. Measurement setup

Measurements were performed in two different RCs. The first one being the National Institute of Standards and Technology (NIST) RC with a volume of 45.20 m³, as shown in Fig. 1(a). The RC has one horizontal and one vertical stirrer, and a turntable to vary antenna positions. A VNA was used, with an IF BW of 1 kHz and, after checking for aliasing, 100 kHz frequency spacing. The calibration reference plane was brought up to the connectors of the antennas by using an N-type electronic calibration module. The antennas used were one dual-ridge horn and one discone antenna, both operated in the frequency range of 0.75 GHz - 3.5 GHz. Both stirrers were varied over 10 different positions each and every measurement used at least \( P = 6 \) antenna positions for a total of 600 mode-stirring samples. The second measurement location is the Eindhoven University of Technology (TUE) RC with a volume of 72.72 m³ and an unfolding wall acting as a stirrer, changing its shape and boundary conditions for every position, while the chamber volume remains the same [15]. 100 different wall positions were used in these measurements, which have been proven by earlier unpublished studies to have low correlation. A different VNA was used, with the same settings as the VNA at NIST. The calibration was performed using a 3.5 mm mechanical calibration kit. Two dual-ridge horn antennas were used, both operated in the same frequency band as the ones at NIST. A uniform window with a 100 MHz BW was used in post-processing for both sets of data to average over frequency. Four experiments were carried out in different configurations, as shown in Table I.

First, four different configurations (experiments 1 a-d in Table I) were measured where a generic 16/3 American Wire...
Gauge (AWG) power extension cord of approximately 10 m (as shown as the orange cord in Fig. 1(b) as part of a larger setup) was placed inside the chamber. In (a) no extra cables were placed in the chamber and in (b) the power cord was placed on the floor and not plugged into a wall socket. In the third configurations the cord was placed on the floor, but plugged into a wall socket. In the fourth configuration the majority of the cord was placed at least $\lambda/2$ away from the walls and floor at the lowest frequency of interest by placing it on polystyrene foam blocks. In all of these cases the cord was unattached to any equipment. A similar power cord was used in the TUE measurement where these four configurations were replicated.

Second, the power cord’s copper conductors were stripped from their outer insulation to determine what part of the cord has the most significant effect on the quantities of interest. First, only the outer insulation was measured (experiment 2 a in Table I). Next, the copper conductors with inner insulation were measured (experiment 2 b). The inner insulation was left on to prevent it from touching the chamber walls.

Third, two types of RF cable were placed inside the chamber to compare their effects with the power cord (experiments 3 a-b in Table I). The cables had a length similar to that of the power cord. The RF cables should be designed to be shielded well and therefore it should have as little effect as possible on the characteristics of the RC. The two cables were placed in the chamber in a similar fashion as the power cord in experiment 1 b-c. The cable was terminated in a 50-Ohm load on both sides to simulate a real use case. In one case a 2.92 mm RF cable with a diameter of 4 mm was measured, and in the other case an N-type RF cable with thicker insulation and a diameter of 1 cm. This measurement was only performed in the TUE RC.

Lastly, a setup for a tunable antenna was tested (experiment 4 in Table I). The setup consisted of three power supplies and power cords and is shown in Fig. 1(b). To keep the results comparable to the power cord measurements, the tunable antenna itself was not added to the setup. This way the effect of solely the extra measurement equipment can be determined.

B. Theoretical model

A model is presented to estimate the effect that the power cord material has on $\tauRC$. To verify whether the copper conductor or the insulation has the most significant effect, the absorbing qualities of the cord insulation and its effect on $\tauRC$ are calculated in this model. The model is based on [4] and [9], which compares the case of an empty chamber with a loaded one by evaluating the losses caused by different factors.

As mentioned in [9], the total Q of a chamber can be described in four power dissipation contributions to the Q as

$$Q_{\text{tot}}^{-1} = Q_1^{-1} + Q_2^{-1} + Q_3^{-1} + Q_4^{-1},$$

with $Q_{1,3,4}$ the contribution of power dissipated in the walls, aperture leakage and antenna loads, respectively, and $Q_2$ the contribution of lossy objects in the RC, given by

$$Q_2 = \frac{2\pi V}{\lambda\langle A_e \rangle_N},$$

where $\lambda$ is the wavelength [m] and $\langle A_e \rangle_N$ the ACS. Due to the fact that the insulation has a much larger skin depth than material thickness because of its low conductivity, the insulation ACS can be approximated by ([4])

$$\langle A_e \rangle_N \approx \frac{AD}{2} \frac{\sqrt{\epsilon_r} \tan \delta}{\epsilon_c},$$

where $A$ is the surface area [$m^2$], $D$ the material thickness [m], $\epsilon_r$ is the relative permittivity of the material and $\tan \delta$ the loss tangent. All factors in $Q_{1,3,4}$ describe the power loss contributions of objects that are always present in the chambers.
in all configurations. By comparing \( Q_{tot} \) with and without the influence of \( Q_2 \), \( \tau_{RC} \) can be calculated for both cases using 
\[
\tau_{RC} = \frac{Q_{tot}}{Q_2}.
\]
To determine the reference \( Q_{tot} \) without the influence of \( Q_2 \), measurements in an empty reference chamber were performed.

The cord insulation is mostly made out of PVC, so the material characteristics in the model are chosen to be \( \epsilon_r = 4 \) and \( \tan \delta = 0.06 \) [16]. It should be noted that inaccuracies can occur because these characteristics are not determined for all frequencies used, and the insulation also consists of other materials, causing deviations in the material parameters.

IV. RESULTS & DISCUSSION

A. Chamber decay time

Fig. 2(a) shows the results of experiments 1 a-d at NIST. The reference chamber measurement was taken at nine different antenna positions and the standard deviation of the measurements, corresponding primarily to the uncertainty due to lack of spatial uniformity, is shown by the error bars. For the sake of clarity, these were only shown for the reference chamber, since the other measurements had similar uncertainty values. A more complete analysis of uncertainty can be found in [17]. There is clearly a significant difference in \( \tau_{RC} \) with the power cord present, with decreases of over 10% at the higher part of the frequency band. Fig. 2(b) shows the results of the same experiments at TUE. Note the difference in the \( \tau_{RC} \) axis compared to the NIST results. All TUE measurements were taken at one antenna position so no standard deviation could be determined for those results. However, repeat measurements have been taken earlier which showed deviations of less than 2% for this component of uncertainty.

The trend of \( \tau_{RC} \) is different for both RCs due to significant differences in chamber size, stirrers, materials, sealing, etc. However, a similar effect of the power cord can be seen in the TUE results, with differences of up to 5% in the lower part of the frequency band. This verifies that power is dissipated in the power cord and therefore affects the chamber decay time of an RC. The effect is less in the TUE results due to differences in chamber losses and the ratio in size between the cord and the chamber, since the TUE chamber is \( \sim 27 \text{ m}^3 \) larger than the one at NIST, while the cord is similar. There are differences of up to 5% between the cord configurations at NIST in the lower part of the frequency band, but these effects are not as significant as the effect of having a power cord in the NIST RC compared to the empty reference chamber case.

Fig. 3 shows the results of experiments 2 a-b, where the copper conductors and outer insulation were measured separately, with (a) the results from NIST and (b) the results expected for all curves.

![Fig. 2](image1.png)  
(a) Results at NIST, \( P = 9 \) for the reference chamber and \( P = 6 \) for the others. Similar uncertainties expected for all curves.

![Fig. 3](image2.png)  
(b) Results at TUE, \( P = 1 \) for all measurement.

![Fig. 2](image3.png)  
(a) Results at TUE, \( P = 1 \) for all measurement.

![Fig. 3](image4.png)  
(b) Results at TUE.

Fig. 2. Experiment 1 a-d, \( \tau_{RC} \) results at NIST and TUE for different cord configurations.

Fig. 3. Experiment 2 a-b \( \tau_{RC} \) results at NIST and TUE of the copper conductor and the outer insulation. (a) includes the insulation model results.
from TUE. Due to changes in setup, the results in Fig. 3(b) are not comparable to those in Fig. 2(b), so the reference chamber measurement, and the model based on it, were not added to the TUE results. However, both results show that the copper conductor with inner insulation has a larger effect on $\tau_{RC}$. The model shows that the insulation should have a negligible effect on $\tau_{RC}$, which matches the measurement results. Therefore it can be concluded that the decrease in $\tau_{RC}$ is most significantly caused by the copper conductor. It has been shown earlier that fields in an RC can couple into transmission lines and cables [18] [19]. The measurement shows that some of the reflected energy in the RC couples into the copper conductor. Due to the large cable length compared to the wavelength at the frequencies under study, it can be expected that the cable supports a large number of modes and, due to its limited quality factor, a wideband behavior. It is expected that these effects are lower for shorter cords, and, as can be derived from (5), also for chambers with higher losses.

Fig. 4 shows the results of experiments 3 a-b, where an RF cable was present in the chamber. Since an RF cable is designed to be properly shielded against environments like an RC, it should not be possible for an electric field to couple into the cable, which is supported by the results. Deviations $<1\%$ are visible due to uncertainties.

Fig. 5(a) shows the results of experiment 4, with the setup shown in Fig. 1(b), where the power supplies and power cords were present in the chamber. The effect of a plugged-in cord on the floor was added too as a reference. The full setup has an even more significant effect on $\tau_{RC}$ compared to the single power cord. Differences of over 20% are visible in this case due to the presence of more power cords, but power is also expected to couple into the power supplies.

B. Coherence Bandwidth

Fig. 5(b) shows the CBW for the case of an empty reference chamber compared to one with a cord or full setup present. Since an RF cable is designed to be properly shielded against environments like an RC, it should not be possible for an electric field to couple into the cable, which is supported by the results. Deviations $<1\%$ are visible due to uncertainties. In this experiment, a power cord being present causes approximately 10% fewer uncorrelated frequency samples. This decrease is approximately 20% for the full setup. For communication signal measurements, the peripheral equipment needs to be taken into account to understand its effect on the CBW and, hence, the independence of frequency samples.

C. Antenna Efficiency

When focus lies in obtaining fast results, antenna efficiencies are often calculated by using a predetermined $\tau_{RC}$, usually determined using a configuration similar to the reference chamber configuration in Fig. 1(a), where no full measurement setup is present. This can cause a deviation in results when using the 2-antenna method described in [13]. Fig. 6 shows the efficiency results for the discone antenna (AUT) with a power cord (experiment 1 b) or a full setup (experiment 4) present in the chamber, with (a) the results calculated with the correct $\tau_{RC}$ and (b) the results calculated with a predetermined $\tau_{RC}$ of an empty reference chamber. When using the time constant of the empty reference chamber while there is peripheral equipment present, $\tau_{RC}$ is overestimated. This leads to an underestimated efficiency, as can be derived from (3). The results show that when using a predetermined $\tau_{RC}$, the presence of a power cord in the NIST RC can lead up to 5% differences, and with a full setup up to 10%. For the sake of brevity, the reference
horn antenna results were not shown, since they were similar.

V. CONCLUSION

In this paper, the effects of peripheral equipment on RC metrics, such as $\tau_{RC}$ and CBW, are presented, together with its effect on antenna efficiency calculations. It has been shown that the presence of a power cord affects $\tau_{RC}$ and CBW, mainly due to the field coupling into the copper conductors of the cord, with differences measured of over 10 %, and over 20 % for a setup consisting of power supplies and power cords. The effect of the equipment on the antenna efficiency is negligible, but it has been shown that the use of a predetermined $\tau_{RC}$ can lead up to 5 % deviations with a power cord present and up to 10 % deviations with a full setup. These percentages are chamber specific and are lower for RCs that have higher losses. This work has shown the importance of taking equipment as seemingly negligible as a power cord into account when configuring the chamber setup before starting a wireless device measurement. This illustrates the need for users to characterize their chambers with the same setup to be used for tests.

REFERENCES


