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Citation for published version (APA):

DOI:
10.1109/TAP.2020.2969883

Document status and date:
Published: 01/06/2020

Document Version:
Accepted manuscript including changes made at the peer-review stage

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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Uncertainty in Reverberation-Chamber Antenna-Efficiency Measurements in the Presence of a Phantom

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Abstract—The effect of a user’s proximity on wireless device performance is critical to test the device under realistic conditions. In this work, we propose and demonstrate an improved uncertainty estimation method for antenna efficiency measurements in a reverberation chamber. The improved method separately computes uncertainties due to the effects of chamber loading by a phantom and the effects of antenna mismatch introduced by this phantom, illustrating the sensitivity of uncertainty to close-proximity user effects. We demonstrate that, while the impact of the phantom may be significant on antenna efficiency, and, it has some influence on the uncertainty in the measurement, its impact on overall uncertainty may be insignificant. This is demonstrated using the two-antenna method in the presence of a phantom close to the antenna under test. We illustrate the method by summarizing the antenna efficiencies with their uncertainties and the impact of the phantom for important communication bands. Due to the large effect of the user on antenna performance, this type of measurement and its uncertainty evaluation is a valuable way to characterize antenna efficiency including user effects.

Index Terms—Antenna Efficiency Measurements, Human Phantom, Measurement Uncertainty, Reverberation Chambers, User Effects, Wireless System

I. INTRODUCTION

With next-generation systems such as 5G, its versatile application scenarios [1]–[4], and expansion of frequency bands [5], [6], the need for fast and accurate characterization methods for mobile devices and their subsystems is continuously increasing. Reverberation chambers are an effective solution to measurements of wireless device metrics such as total radiated power (TRP) [7], [8] and total isotropic sensitivity (TIS) [8]–[10], as they provide a way to obtain these metrics without the need for three-dimensional scans. The antenna efficiency is a critical antenna metric, and must also be known for TRP and TIS measurements [7]–[12]. To date, various methods to measure the antenna efficiency have been proposed [13]–[22].

One of the areas that will become even more relevant, for example for smartphones and body-wearables, is the effect of the user’s proximity to the device under test (DUT) performance, which we refer to here as the “user effect.” Including these effects in the measurement can help antenna designers to optimize their design in the actual use-case scenario. Some studies on the effect of the user on the antenna performance have been performed [23]–[29], but a detailed reverberation chamber study with uncertainty analysis has yet to be performed. The effect of an antenna placed close to an absorbing material is discussed in [30], where it is shown that the absorbing material prevents part of the radiation from interacting with the chamber walls and stirrer(s). In addition to the actual late-time [20], [31] loading of the chamber by the absorbers, thereby changing the chamber’s Q or time constant, they prevent energy from coupling from one antenna into the other antenna during chamber build-up [30], an effect that is also known as the Proximity Effect [6]. From an antenna efficiency measurement viewpoint, the absorbing material acts as an additional antenna load and, thus, results in a different antenna efficiency and input impedance than its free-space behavior. We could view this as a new antenna under test (AUT). On the surface, it may seem like the efficiency measurement uncertainty should not depend on the AUT. However, we can identify two distinct mechanisms that could impact the uncertainty. First, the inclusion of a phantom near the AUT will load the chamber, which may increase the measurement uncertainty due to a local decrease of spatial uniformity [8], [12], [30], [32]. While it has been shown that a decrease in chamber Q by slightly loading it outside of the working volume can improve the uniformity [33]–[36], in the situation investigated here the loading is next to an AUT. Second, the uncertainty in the efficiency due to the VNA and calibration will depend on the DUT’s impedance, in this case the impedance of the AUT with or without the phantom.

In this work, we will investigate how the loading of a reverberation chamber with a phantom influences the uncertainty of antenna efficiency measurements, accounting for both mechanisms, using the two-antenna method introduced in [20], [37]. We introduce a new uncertainty estimation method, and investigate for the first time effects of a phantom on it. We will focus on 5G’s sub-6 GHz range [5], covering 750 MHz to 6 GHz. Results are presented for both the radiation efficiency $\eta_{\text{rad}}$ and the total efficiency $\eta_{\text{tot}}$, which are the efficiencies excluding and including mismatch losses, respectively. To this end, we introduce a new method to estimate the efficiency measurement uncertainty. This combines the NIST Microwave Uncertainty Framework (MUF) [38] with uncertainty due to measurement reproducibility based on the use of independent realizations. The MUF allows us to account for the impact of the VNA’s uncertainties on the antenna efficiency uncertainties, which will be shown to depend on the AUT’s impedance. The method accounts for these Type B (deterministic) VNA uncertainties as well as Type A (determined using statistical methods) effects such as spatial uniformity,
limited number of samples, and cable movement between antenna positions. Previous methods did not account for VNA (calibration) uncertainty [20], [39] or demanded low-Rician-K-factor environments [22], [40] for validity. We show that the former has a significant contribution to the uncertainty, while the latter will become problematic when the chamber is loaded, which is required for example when determining the efficiency of an antenna in the presence of a phantom. In addition, the frequency-dependence of the uncertainty has yet to be shown. Our new uncertainty estimation method does not make assumptions on the chamber configuration, while still accounting for VNA uncertainties, and will be demonstrated over a wide frequency band.

The new uncertainty estimation method allows us to compare several reverberation-chamber configurations and study the resulting uncertainty as a function of frequency. We will introduce a phantom into the chamber, first far away from both the measurement antenna and the AUT, and then move it stepwise closer to the AUT. This will be compared to the conventional case, without a phantom present in the reverberation chamber. From the results, we can conclude that the effect of loading by the phantom on the measurement uncertainty of the two-antenna efficiency method is very small, even when the antenna efficiency is significantly affected by the phantom. We show that the two-antenna method can be used to determine the efficiencies of an AUT including user effects, provided that the change in chamber time constant $\tau_{RC}$ is accounted for in the calculations.

This paper starts by describing the experiments that we have performed and their setup. Then, we introduce our proposed uncertainty estimation method in Section III. In Section IV we study the impact of the phantom, while the work is concluded in Section V.

II. EXPERIMENT AND CHAMBER SETUP

All measurements were performed in one of NIST’s reverberation chambers. This is a 4.27 m x 3.65 m x 2.90 m chamber with one horizontally and one vertically rotating paddle, as shown in Fig. 1a. The chamber also includes a turntable to perform position stirring, which is necessary for wireless tests in loaded chambers [8], [12]. There were always two antennas in the reverberation chamber. The measurement antenna was a dual-ridge horn antenna (DRHA) pointed towards the horizontal paddle to minimize the $K$-factor, which will be referred to as the DRHA measurement antenna. The second antenna was a discone AUT, which was chosen for its omnidirectional-like properties in order to resemble a mobile device’s far-field behavior as closely as possible, while maintaining a large measurement bandwidth. It was placed on the reverberation chamber’s turntable, into which a rotary joint was installed to minimize the effect of cable movement. In order to study the impact of the phantom on both the estimate of antenna efficiency and corresponding measurement uncertainty, we will look at four different configurations:

(A) No phantom is present in the chamber, as shown in Fig. 1(a) and 2(a). This is the ideal case, which one would normally use to measure antenna efficiency.

(B) A phantom is present in the chamber, but far away from both antennas and in a fixed location, as shown in Fig. 1(b) and 2(b). This case is introduced to study the...
effect of loading the chamber lightly using the phantom, with the phantom far away from the discone AUT and DRHA measurement antenna.

(C) The phantom is placed close to the discone AUT, as illustrated in Fig. 1(c) and 2(c). The phantom is sufficiently close (in the discone AUT’s free-space near-field) to affect the discone AUT’s efficiencies and input match. In this case the position of the phantom is fixed with respect to the discone AUT, meaning that both move together on the turntable and/or polarization change for independent realizations, as will be explained later in this section. The center rod of the discone AUT is located approximately 7.5 cm from the phantom’s shell.

(D) The discone AUT is placed such that it is actually touching the phantom. This is shown in Fig. 1(d), and more detailed for the high-band and low-band in Fig. 2(d) and 3, respectively. This is a very similar configuration to C, but with a stronger impact of the phantom on the discone AUT performance that we used as compared to configuration C.

Since the discone AUTs have a smaller frequency range than our desired 0.75-6 GHz 5G range, we used two different discone antennas to cover 0.75-3.5 GHz (referred to as low-band) and 2.8-6 GHz (referred to as high-band). Note that these bands overlap, allowing us to directly compare measurements with different discone AUTs in the same frequency range. All measurements were performed using a VNA with an N-type electronic calibration module. We chose a frequency point spacing of 100 kHz, an IF bandwidth of 1 kHz, a dwell time of 10 µs. The calibrations were performed at the antenna N-type connector interfaces. The phantom used was a SPEAG SAM-V4.5BS\(^1\) homogeneous anthropomorphically shaped human head phantom. Please refer to [6], [41], [42] for details on the phantom’s shape and filling material properties.

Throughout this paper we will make references to independent realizations and/or mode-stirring samples. This is meant to refer to approximate independence, which is verified by measuring the coherence angles of the turntable and paddles. The half-width coherence angles, found using the autocorrelations of the platform [43], horizontal paddle and vertical paddle are below a 0.3 threshold at 9, 7 and 9 degrees, respectively. These are the worst-case angles at the low end of our frequency range, which rapidly decrease for increasing frequency. Since the steps chosen for the measurements are significantly larger (and therefore their correlation lower), as indicated below, approximate independence is assumed and referred to as ‘independent’.

For all configurations, we created \( P = 9 \) [12], [44] independent realizations by changing the turntable (and therefore discone AUT) position and/or changing the discone AUT’s polarization. Each independent realization consisted of 10 positions for each of the paddles, resulting in a total of \( N = 100 \) independent stepped mode-stirring samples at each frequency point for each independent realization, configuration and band. All parameters (the efficiencies, chamber time constant, and power reference transfer function) can be calculated for each independent realization. The best estimate is then either the average of the \( P \) realizations, or obtained by also averaging across the turntable positions at an earlier stage in the calculations. The calculation methods for each of the results are described in the next sections.

III. UNCERTAINTY IN ANTENNA EFFICIENCY

A. Antenna Efficiency Calculation

The uncertainty estimations will show the impact of the phantom on the efficiency measurement uncertainty, and provide insight into configuration requirements for performing efficiency measurements using the two-antenna method [20]. For the purpose of this work we will assume that the two-antenna method does not make any approximations with respect to antenna radiation pattern, ideality of enhanced backscattering, antenna (mis)match behavior, or positioning. These effects will be the topic of future research. In addition we assume that the positioning in configurations C and D of the discone AUT with respect to the phantom is fully representative of the desired positioning, i.e. the effect of deviations in the antenna positioning with respect to the phantom are not taken into account in the uncertainty. For the reader’s convenience, we briefly summarize the two-antenna efficiency measurement method. It is based around a comparison of time-domain and frequency-domain quality factors. Two antennas are placed inside the reverberation chamber and connected to two ports of a VNA. Then, the efficiencies can be calculated using [20]:

\[
\eta_{\text{MEAS}}^{\text{tot}} = \sqrt{\frac{8\pi^2 f^2}{2\pi f^2}} \langle |S_{21} - \langle S_{21} \rangle_N |^2 \rangle \langle |S_{11} - \langle S_{11} \rangle_N |^2 \rangle / \langle |S_{22} - \langle S_{22} \rangle_N |^2 \rangle,
\]

\[
\eta_{\text{MEAS}}^{\text{rad}} = \frac{\eta_{\text{MEAS}}^{\text{tot}}}{1 - \langle |S_{11} |^2 \rangle},
\]

where \( S_{11} \) should be replaced by \( S_{22} \) and vice versa to obtain the efficiencies for the discone AUT, \( \eta_{\text{MEAS}}^{\text{tot}} \) and \( \eta_{\text{MEAS}}^{\text{rad}} \). V [m\(^3\)]

\(^1\)The use or illustration of specific products is for clarification only and does not imply endorsement by NIST. Other products may work as well or better.

![Fig. 3. Configuration D with the low-band discone AUT.](image)
denotes the chamber volume, \( f \) [Hz] is the measurement frequency, \( c_0 \) [m/s] is the speed of light in a vacuum, and \( \tau_{RC} \) [s] is the chamber time constant. Note that, though the dependence is not shown explicitly for readability, the chamber time constant, the S-parameters and the efficiencies are all functions of frequency. For convenience, we have used \( \langle \cdot \rangle_N \) to indicate taking the ensemble average over the \( N \) paddle positions, while using \( \langle \cdot \rangle \) to indicate the ensemble average over paddle positions and an \( F = 100 \) MHz band. This is possible due to the wide-band characteristics of the antennas that are applied, as well as the chamber characteristics. A study of the effect of this averaging band showed that its smoothing has very little effect on the results since it is still a small bandwidth compared to our measurement frequency range, while the use of a wider bandwidth offers more independent samples to improve the estimate. For the best estimate, \( \langle \cdot \rangle \) also indicates averaging over turntable positions. We will use this notation (indicating which average is taken if it is not indicative of all dimensions) throughout this paper. Thus, we average only over \( N = 100 \) paddle positions when indicating \( \langle \cdot \rangle_N \), over \( N = 100 \) paddle positions and an \( F = 100 \) MHz band when indicating \( \langle \cdot \rangle \) for an independent realization, while averaging over \( N = 100 \) paddle positions, an \( F = 100 \) MHz band and \( P = 9 \) independent realizations when indicating \( \langle \cdot \rangle \) for the best estimate.

It is noteworthy that this two-antenna efficiency measurement method was developed for unloaded or slightly loaded RC’s satisfying the well-stirred condition [20, 45]. Nonetheless the two-antenna efficiency measurement method should remain valid for a (lightly) loaded chamber, as is the case with our phantom, since the loss due to the loading cannot be distinguished from the chamber’s loss, and the chamber’s Q factor is expected to remain sufficiently high to achieve a good uniformity. Indeed, it could even be improved by an increased modal overlap if the chamber’s unloaded Q is too high [33–36]. However, in the case of a phantom the chamber is loaded inside the working volume. A comparison between the results obtained in configurations A and B will serve to validate the applicability of the two-antenna efficiency measurement method when the phantom is placed inside the working volume. For configurations C and D, we can view the antenna including the phantom as one single DUT [30]. However, in its derivation, the two-antenna efficiency measurement method implicitly assumes that the two antennas that are measured do not introduce surplus losses (introduced by e.g. antenna carriers or modes in the antenna materials other than the normal antenna modes) into the chamber close to the DUT. Therefore a distinction should be made between the losses introduced by the antenna’s operating modes (i.e. the user effect), and the losses due to the loading of the chamber presented by the phantom.

We can distinguish these loss mechanisms using the time constant, as it is an estimate of the chamber’s losses [20, 30, 46, 47], in this case including the slight loading of the chamber introduced by the phantom, as opposed to the user effect. Any deviation from this would be visible as a difference between the time constants in configurations B, C and D, which will be shown to be indistinguishable from one another in Section IV-A. Stated another way, the losses in the chamber introduced by the phantom are accounted for within the time constant, as it would account for a change of chamber geometry, material or paddle, and the efficiency obtained using the two-antenna method includes the additional losses introduced by the discone AUT’s vicinity to the phantom. Thus, we can extract the desired antenna efficiencies accounting for the user-effect from configurations C and D.

Referring to (1) and (2), if we assume the uncertainty in the measurement of the chamber volume is insignificant (which we expect to be the case for our large chamber volume), the only uncertainty contributions are in the S-parameters and the chamber time constant \( \tau_{RC} \). As we show in Section III-B, the uncertainty in the radiation efficiency is sensitive to the antenna mismatch, resulting in a significant difference in uncertainty for configurations A and B versus C and D. The chamber time constant is determined by calculating the power-delay-profile (PDP) from \( S_{21} \) as PDP(t) = \( \langle \text{IFFT}[S_{21}(f)]^2 \rangle_N \), for \( n = 1 \ldots N \) mode-stirring samples and then fitting an exponential decay on an 0.4-8 \( \mu \)s interval. As will be shown in Section IV-A, the contribution of \( \tau_{RC} \) to the uncertainty is insignificant for all configurations that we studied. This leaves only uncertainty components in the magnitudes of the stirred component of the S-parameters \( |S_{21} − \langle S_{21} \rangle_N | \) and in the mismatch terms to be incorporated in the uncertainty estimation, as discussed in Section III-B.

**B. Uncertainty Estimation**

Our approach to obtain the measurement uncertainty on the antenna (radiation and total) efficiencies is based on splitting the overall uncertainty into two components: Type B errors derived from the VNA calibration and measurement, with a standard deviation \( u_{VNA} \), and Type A uncertainty due to statistically determined effects (from the diagonal of the estimated covariance matrix) with standard deviation \( u_{COV} \). The frequency dependence of both, though not explicitly shown, is carefully maintained throughout the process in both components. In order to estimate \( u_{VNA} \), we utilize the MUF.

To account for Type A uncertainty contributions (chamber uniformity, limited number of samples, measurement noise, cable movement between measurements), \( u_{COV} \) is estimated by first determining the best estimate for the efficiency \( \eta \) as described in Section III-A. Next, we can estimate the standard uncertainty for each independent realization as:

\[
u_{COV} = \sqrt{\frac{1}{P-1} \sum_{p=1}^{P} (\eta_p - \bar{\eta})^2},\tag{3}\]

where \( \eta_p \) denotes the estimated antenna efficiency at independent realization \( p \), while \( \bar{\eta} \) denotes the best estimate for the antenna efficiency. This provides us with one uncertainty component that accounts for Type A errors, such as spatial uniformity in the chamber, uncorrelated measurement noise, and finite number of mode-stirring samples (assuming their effect uncorrelated between the realizations). Earlier estimates were based on an estimated deviation of enhanced backscattering constant \( c_b \) [20], or a good chamber uniformity had to be assumed [22, 40].
Concerning Type B uncertainties, we use the MUF to obtain the contribution of the VNA to the uncertainty. It determines uncertainties with their distributions for the electronic calibration unit we used, and then propagates these uncertainties to the antenna efficiency results using sensitivity and Monte Carlo analysis methods in parallel. Using our approach with the MUF, we can account for the uncertainty in the calibration as a function of frequency, as opposed to earlier estimations, where an empirically obtained change in $|S_{21}|^2$ over time is used [20], or the frequency-dependence is averaged out [22]. The estimation of $u_{VNA}$ in our procedure consists of three steps:

1) **Obtain calibration coefficients and uncertainties of the electronic calibration unit using the MUF** [48]. To this end, the VNA is used with the same settings as for the actual experiment, and calibrated with the electronic calibration unit. Next, mechanical standards are measured. Using circuit models of the mechanical standards, the calibration coefficients and uncertainties for the electronic calibration unit are determined.

2) **Apply the calibration to a set of data, correcting the data and adding uncertainties to each mode-stirring sample.** Because of the time-consuming nature of this step, and because we do not expect the VNA uncertainty to change from realization to realization, this was done for only one realization for each of the configurations in both bands, for all configurations.

3) **Propagate the uncertainties in each mode-stirring sample to the resulting total and radiation efficiencies.** This provides us with the VNA uncertainty contribution associated with the VNA calibration standards on the efficiencies.

Note that the radiation efficiency in (2) will be higher than the total efficiency when the antenna mismatch is nonzero. In addition, the uncertainty in the estimate of $\eta_{rad}$ may be more sensitive to nonzero values of $S_{11}$ than the uncertainty in the estimate of $\eta_{hot}$. This is explained as follows. According to [49] (see equation (10)), the variance in the estimate of a function $f$ with input $x$ may be given by:

$$\sigma_f^2 = \left( \frac{\partial f}{\partial x} \right)^2 \sigma_x^2,$$

where the first term on the right side of the equation is the square of the “sensitivity coefficient” and the second term corresponds to the square of the measurement uncertainty. To find the sensitivity coefficient for $\eta_{rad}$, we denote:

$$f = \frac{\eta_{hot}}{1 - |\langle S_{11} \rangle|^2}.$$  \hfill (5)

Taking the partial derivative with respect to $|\langle S_{11} \rangle|$ and assuming $|\langle S_{11} \rangle| \ll 1$, we apply a Taylor expansion to obtain

$$\frac{\partial f}{\partial |S_{11}|} \approx \frac{\eta_{hot}}{|\langle S_{11} \rangle|^2} \left( 1 + |\langle S_{11} \rangle|^2 \right) = 2 \eta_{hot} |\langle S_{11} \rangle|.$$  \hfill (6)

This equation shows that the sensitivity of the uncertainty in $\eta_{rad}$ is a linear function of the value of $|\langle S_{11} \rangle|$. Note that when the nonlinearity of $f$ is significant, higher-order terms in the Taylor series expansion must be included. Combining this term with the VNA measurement uncertainty on $\eta_{hot}$, we have:

$$\sigma^2_{VNA, \eta_{rad}} \approx (2|\langle S_{11} \rangle|)^2 \sigma^2_{VNA, \eta_{hot}},$$

showing that the VNA measurement uncertainty on $\eta_{rad}$ will depend on the antenna’s input reflection. The NIST MUF will account for both terms in its representation of uncertainty in $\eta_{rad}$. The measured input reflection coefficients of the discone AUTs are shown in Fig. 4. As one would expect, we observe a change in input reflection coefficient between configurations C and D with respect to A and B, but not between A and B. Thus, we can expect the VNA measurement uncertainty to change between configurations A and B with respect to configuration C or D. Note that the change in the antenna input reflection coefficients is smaller than would likely be the case for actual mobile antennas due to the discone AUT geometries, as discussed in more detail in Secion IV-C.

Now we can estimate the overall measurement uncertainty by taking the root-sum-of-squares [50] as:

$$u_C = k \cdot \sqrt{u^2_{VNA} + u^2_{COV}},$$

where $k$ is the coverage factor. We obtain the coverage factor from the effective degrees of freedom, which is in turn obtained using the Welch-Satterthwaite equation [49], [50]. Note that, though the indices are omitted for brevity, this is still a function of frequency, and is calculated for each of the configurations and bands as well as for total and radiation efficiency separately. In the next section, we will use this uncertainty estimation to study the effect of including a phantom in the efficiency measurement, and whether extra care has to be taken when performing those measurements. In particular, we will show whether the uncertainty due to lack of spatial uniformity in the chamber increases significantly when introducing a phantom, and whether that effect is significant when compared to the VNA uncertainty.
TABLE I
\(\sigma_{G_{\text{ref}}}, \sigma_{\tau_\text{RC}}\) FOR THE FOUR CONFIGURATIONS, AVERAGED OVER EACH OF THE TWO FREQUENCY BANDS. THE RELATIVE ERROR IN THE TIME-CONSTANT IS ALSO GIVEN BETWEEN BRACKETS.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>(\sigma_{G_{\text{ref}}} [\text{dB}])</th>
<th>(\sigma_{\tau_\text{RC}} [\text{ns}]) (in mean [%])</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low-band</td>
<td>High-band</td>
</tr>
<tr>
<td>A</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>B</td>
<td>0.008</td>
<td>0.006</td>
</tr>
<tr>
<td>C</td>
<td>0.009</td>
<td>0.007</td>
</tr>
<tr>
<td>D</td>
<td>0.012</td>
<td>0.009</td>
</tr>
</tbody>
</table>

Fig. 5. Reference power transfer function \(G_{\text{ref}}\) for the four configurations over both frequency ranges. Configurations B, C and D (with the phantom in the chamber) are overlapping, while Configuration A (unloaded chamber) deviates. The low-band and high-band match in their common ranges.

IV. IMPACT OF PHANTOM ON ANTENNA EFFICIENCY AND ITS MEASUREMENT UNCERTAINTY

A. Chamber Characteristics

Before proceeding to the antenna efficiency measurements, we first perform a chamber characterization for the four configurations to identify the effect of the phantom on chamber uniformity and loss. This includes an evaluation of the chamber’s reference power transfer function \(G_{\text{ref}}\), calculated as [8], [12], [51]:

\[
G_{\text{ref},p} = \frac{\langle |S_{21}|^2 \rangle_{N,F}}{\eta_{\text{MEAS},\text{AUT}}}.
\]

\[
G_{\text{ref}} = \frac{\langle G_{\text{ref},p} \rangle}{\langle \eta_{\text{MEAS},\text{AUT}} \rangle},
\]

where \(\eta_{\text{MEAS}}\) and \(\eta_{\text{AUT}}\) are taken from the best estimate efficiencies determined in Section IV-C. The standard deviation of \(G_{\text{ref}}\) can be used as a metric for the spatial uniformity of the averaged field in the reverberation chamber [8], [12]. We show the results for \(G_{\text{ref}}\) in Fig. 5, and give its estimated standard deviation in Table I. We can observe that the results for \(G_{\text{ref}}\) for configurations B, C and D overlap, while configuration A is higher. This is due to the energy loss in the phantom. As expected, the phantom (slightly) loads the RC, causing a decrease in \(G_{\text{ref}}\). Furthermore, all results connect in the frequency range that is covered by both high and low bands. As expected, Table I shows an increase in \(\sigma_{G_{\text{ref}}}\) for increasing configuration letter in both the low and high bands, indicating a decreasing spatial uniformity when the phantom is introduced or moved closer to the discone AUT. Note however that all standard deviations of \(G_{\text{ref}}\) are 0.012 dB or less, indicating a very good spatial uniformity for all configurations. A previous study found estimated \(\sigma_{G_{\text{ref}}}\) results between 0.04 dB and 0.21 dB in the PCS band (1.8-1.95 GHz) for an unloaded RC [51], but used only a single paddle with 72 positions (in a different RC). For the frequency range above 400 MHz, the IEC standard only requires the standard deviation to be below 3 dB [13]. The use of multiple paddles, in addition to frequency stirring, allows us to obtain more independent samples and thereby to improve uniformity. While not explicitly shown for conciseness, our estimated \(\sigma_{G_{\text{ref}}}\) over frequency peaks at a worst-case for all bands and configurations at nearly 0.035 dB. The use of a rotary joint also improves our \(\sigma_{G_{\text{ref}}}\), as it minimizes variations due to cable movement.

The results for the time constant \(\tau_{\text{RC}}\) are shown in Fig. 6. Again, the bands connect very well for all configurations, and again configurations B, C and D are overlapping and lower than configuration A, as expected. The estimated standard deviation is given in Table I, where the standard deviation of the time constant for a single position is shown in nanoseconds. Since we use the mean (best estimate) of \(\tau_{\text{RC}}\) of all positions for later measurements, this reduces the standard deviation to the relative uncertainties (standard deviation divided by the best estimate) given in the table between brackets. We choose to show the relative uncertainty here, as it is the deviation in \(\tau_{\text{RC}}\) that impacts the antenna efficiency as opposed to its absolute value. As in [20], the resulting relative errors in the mean of \(\tau_{\text{RC}}\) are deemed insignificant, and not taken into account any further. However, note that the phantom has a significant impact on the reverberation chamber’s time constant, so a time
constant obtained with the phantom present must be used when testing with the phantom to obtain the correct efficiency. As one would expect, the location of the phantom does not appear to have a significant effect on the obtained time constant, yet for all configurations the corresponding time constant is used in this work to be completely consistent.

B. Uncertainty Components

In order to study which effects are affected by the phantom and how much the Type A and Type B uncertainties each contribute to the overall uncertainty, we will show the two uncertainty components $u_{\text{COV}}$ and $u_{\text{VNA}}$ separately. Since the behavior of $u_{\text{COV}}$ does not show a clear trend over frequency, we have chosen to present its results averaged over each of the two bands, as seen in Table II where we are representing the uncertainties on the antenna efficiencies in percent. The uncertainty contributions in this table are all between 0.45% and 0.75%, which is very small compared to the antenna efficiencies, which are always higher than 50%. There are no clear trends to be observed when comparing the four configurations or comparing the DRHA measurement antenna with the discone AUTs. Though the difference is small, it should be noted that the estimated uncertainty component due to Type A effects is always slightly higher for the radiation efficiency than for the corresponding total efficiency. This is due to the mismatch compensation applied to the radiation efficiency (2), which introduces an additional parameter into the equation. In addition, $\eta_{\text{rad}}$ is higher than $\eta_{\text{tot}}$ by definition: the power accepted by the antenna can never be larger than the available power at the antenna interface.

Next, we study the VNA uncertainty $u_{\text{VNA}}$. Since this is a Type B uncertainty, it does show clear and reproducible frequency dependence and is therefore presented in graphs. The results are shown in Fig. 7 and 8 for the DRHA measurement antenna and the discone AUTs, respectively. For the DRHA measurement antenna the dashed curves represent radiation efficiency, while the solid curves indicate the result for total efficiency.

For the DRHA measurement antenna, shown in Fig. 7, there are two clear sets: one for the radiation efficiency, and one for the total efficiency. Note that the two bands also match in their overlapping frequency range. The VNA uncertainty contribution is a function of the antenna’s impedance - the impact on the efficiency of an error in the calibration will vary depending on the actual impedance at the reference plane. Since the phantom is never placed near the DRHA measurement antenna, it does not have a noticeable impact on the VNA uncertainty for that antenna. Over nearly the entire frequency range, the VNA uncertainty contribution to the radiation efficiency is larger than that for the total efficiency. Again, this is due to the addition of another S-parameter component to (2), and the radiation efficiency being (by definition) higher than the total efficiency.

For the discone AUTs we can observe similar effects in Fig. 8. The curves between the high-band and the low-band do not connect, since a different discone AUT is being used (resulting in a different impedance). However, the curves for configurations A and B, the cases in which the phantom is not present or far away from the discone AUT, are always on top of one another. Configurations C and D deviate from that set and one another, as the phantom changes the antenna’s input impedance, which, in turn, changes the VNA uncertainty. It is noteworthy that, as expected from our discussion on the sensitivity of $u_{\text{VNA}}$ in Section III-B, $u_{\text{VNA}}$ tends to be lower for better matched antennas. This can be quite clearly observed by comparing the high-band results for configuration D, with those for configurations A, B and C. As shown in Fig. 4, the high-band discone AUT happens to be better matched between 3 and 3.5 GHz in configuration D, resulting in a lower $u_{\text{VNA}}$ for configuration D in this band.

C. Antenna Efficiencies

Now that we understand the individual uncertainty components, we will present the measured efficiencies for the configurations along with their expanded uncertainties using (8). We show the best estimate (i.e. the result calculated using all discone AUT positions), and error bars represent the 95% confidence interval obtained using (8). Therefore this uncertainty accounts for both the Type A and Type B contributions, as well as the effective degrees of freedom.

The total efficiency and the radiation efficiency obtained for the DRHA measurement antenna are shown in Fig. 9(a) and 9(b), respectively. Since no change was introduced into the DRHA measurement antenna, and the phantom was always off its main axis, all results and bands should overlap. The results for both efficiencies demonstrate that all configurations and bands are indeed within the respective 95% confidence bounds. This validates that the two-antenna method works in the presence of a small phantom in the reverberation chamber, provided that the additional losses are accounted for in $\tau_{\text{RC}}$. Especially at the high frequency end, it may seem like the uncertainties are over-estimated, since the different configurations are within a far smaller margin than the error.


TABLE II

ESTIMATED STANDARD UNCERTAINTIES DUE TO TYPE A UNCERTAINTIES FOR THE FOUR CONFIGURATIONS, AVERAGED OVER THE TWO FREQUENCY RANGES.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>In Radiation Efficiency</th>
<th>In Total Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DRHA</td>
<td>AUT</td>
</tr>
<tr>
<td></td>
<td>Low-band</td>
<td>High-band</td>
</tr>
<tr>
<td>A</td>
<td>0.50</td>
<td>0.52</td>
</tr>
<tr>
<td>B</td>
<td>0.45</td>
<td>0.46</td>
</tr>
<tr>
<td>C</td>
<td>0.70</td>
<td>0.56</td>
</tr>
<tr>
<td>D</td>
<td>0.48</td>
<td>0.48</td>
</tr>
</tbody>
</table>

![Graphs](image)

Fig. 8. $\mu_{\text{NA}}$ for (a) the discone AUTs total efficiency and (b) the discone AUTs’ radiation efficiency, with an inset zooming in on the frequency range where the low-band and high-band results are both available and not overlapping. Eight curves (four configurations, two bands) can be seen in each inset. The curves for the radiation efficiency tend to show a higher uncertainty than those for the total efficiency, as expected.

bars. However, the error bars indicate the overall uncertainty, including Type B contributions, as opposed to the Type A contributions (and impact of the phantom) that are tested between the different configurations.

As one may expect, the efficiencies obtained for the discone AUTs show more difference between the four configurations. The total and radiation efficiencies are shown in Fig. 10(a) and 10(b), respectively. Configurations A and B, where the phantom is far away from the discone AUTs, agree within their 95% confidence intervals. The two bands do not connect for any of the configurations since different discone AUTs are used, exhibiting a different efficiency. Both the total and radiation efficiencies decrease when the phantom is moved close to the discone AUTs, and again when the phantom is touching the discone AUTs. The results for configurations C and D are outside the 95% confidence intervals of the other cases and one another, demonstrating that the impact of the phantom on the antenna efficiency is significant compared to the efficiency measurement uncertainty. We can conclude that the change in both radiation and total efficiency may indeed be measured in the reverberation chamber using the two-antenna method.

While most ripple effects are due to the mismatch loss of the antennas, and are therefore less strongly visible in the radiation efficiencies, some frequency-dependence of the radiation efficiencies remains for the DRHA measurement antenna and the low-band discone AUT. In order to verify that this is real antenna behaviour and not a measurement artefact, we investigated the separately calculated radiation efficiency results for all independent realizations, which do not show significant deviations from one another. Calibrations were re-done at least once during each set of independent realizations due to measurement time, and between configurations. In addition, in the frequency range where both the low-band and the high-band discone antennas are measured, the high-band discone does not show this ripple-like characteristic, while the low-band discone does (Fig. 10b). Moreover, the ripple does not occur with the same frequency periodicity for the DRHA measurement antenna and discone AUT, and the frequency periodicity is at least an order of magnitude different from any of the RC’s or calculation bandwidths. Finally, the RC is extremely over-moded at these frequencies. Combined with the results for Configuration A and Configuration B always being within one another’s 95% confidence intervals as discussed earlier, we therefore expect that this ripple-like radiation efficiency is the antenna behavior itself when it
represents the use-case scenario of a smartphone. While the discone AUTs are of course not completely representative for the use-case scenario of a smartphone, it demonstrates the general principle that this type of measurement can help antenna designers to optimize their design in the actual use-case scenario. While usually the user effects are only analyzed for the specific absorption rate (SAR), an earlier study using a phantom with a mobile phone resulted in losses in the phantom between 1.5 dB (19%) and 5.8 dB (74%) derived from TRP measurements in the EGSM 900 and 1800 bands, respectively [25]. These effects are even more pronounced than they are with our discone AUTs, which are never as close to the phantom as a mobile phone antenna due to their shape. In addition, their strongest reactive near-fields will be away from the edges that are touching the phantom, resulting in less strong effects on both efficiency and input reflection coefficient than in actual mobile antennas. The latter are usually extremely compact, close to a ground plane or similar, and could be separated from the user by only a thin polyester cover [52]. While this effect is qualitatively implied. 

occurs. Our hypothesis for this behaviour is that in order to arrive at an extremely wideband antenna, it is inevitable to create several internal resonances during the antenna design (e.g. quarter-wave and half-wave resonances), as can also be observed from the antennas’ input impedances. These increase the bandwidth, while decreasing the radiation efficiency at their resonance due to the creation of a high reactive near-field and strong currents. This effect will be the topic of future research.

Since the radiation efficiency also shows a significant decrease when the phantom is close to the discone AUT, the loss cannot be recovered by the application of an adaptive matching circuit (i.e. recovering the mismatch loss). The phantom changes the antenna’s input reflection coefficient, but the phantom also dissipates part of the energy accepted by the antenna. While the discone AUTs are of course not completely representative for the use-case scenario of a smartphone, it
by the SAR, it is useful to show quantitative antenna effects. Not only does the user effect present issues for SAR, it also results in a reduced TIS and TRP when a smartphone is used in its intended application, unless taken into account in the design.

V. Conclusion

In this work, we have introduced a new method to estimate the uncertainty (as a function of frequency) of antenna efficiency measurements using the two-antenna method in a reverberation chamber. We have applied the method to demonstrate that the impact of a phantom head on the measurement uncertainty is negligible. In addition, we have shown the contributions of the Type B VNA uncertainty and Type A effects separately. By performing a sensitivity analysis and using empirical results we demonstrated that, for the cases we studied, the impact of the VNA’s uncertainty on the estimated antenna efficiency uncertainty can change when introducing a phantom, which was especially visible in upper section of our frequency range. We then verified that the two-antenna method can be applied in the presence of a phantom, provided the additional losses are accounted for in the chamber time constant. It is not necessary to adopt position stirring for the common configurations we presented. The results allowed us to demonstrate the impact of a phantom head on both the total and radiation efficiencies for a set of antennas. Since the phantom head may have a significant effect on antenna efficiency indeed, this type of measurement and uncertainty evaluation will be crucial for future smartphones and body-wearables. Ideally, measurements including a phantom should be included in the design cycle to allow for optimized designs in their actual usage scenario. Future work will assess the impact of more heavily loading a chamber on antenna efficiency measurement uncertainty, relevant to the testing of large form factor devices.

REFERENCES


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