



UNIVERSITÀ POLITECNICA DELLE MARCHE
Repository ISTITUZIONALE

Characterization of Reverberation Chambers at 60 GHz for Wireless Device Testing

This is the peer reviewed version of the following article:

Original

Characterization of Reverberation Chambers at 60 GHz for Wireless Device Testing / Tili, P., De Leo, A., Bastianelli, L., Moglie, F., Primiani, V.M.. - (2026). (20th European Conference on Antennas and Propagation, EuCAP 2026 Dublin 19 - 24 April 2026) [10.23919/EuCAP68105.2026.11612257].

Availability:

This version is available at: 11566/363192 since: 2026-09-21T06:42:58Z

Publisher:

IEEE

Published

DOI:10.23919/EuCAP68105.2026.11612257

Terms of use:

The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. The use of copyrighted works requires the consent of the rights' holder (author or publisher). Works made available under a Creative Commons license or a Publisher's custom-made license can be used according to the terms and conditions contained therein. See editor's website for further information and terms and conditions.

This item was downloaded from IRIS Università Politecnica delle Marche (<https://iris.univpm.it>). When citing, please refer to the published version.

Publisher copyright:

IEEE - Postprint/Author's Accepted Manuscript

©2026 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works. To access the final edited and published work see 10.23919/EuCAP68105.2026.11612257

(Article begins on next page)

Characterization of Reverberation Chambers at 60 GHz for Wireless Device Testing

Paola Tili*, Alfredo De Leo*, Luca Bastianelli*, Franco Moglie* Valter Mariani Primiani*

Department of Information Engineering, Università Politecnica delle Marche, Ancona, Italy, p.tili@univpm.it

Abstract—Reverberation chambers (RC) have been widely used to perform Electromagnetic Compatibility (EMC) testing due to their statistically uniform, isotropic, and well-scattered fields. Recently, because they can emulate realistic multipath propagation environments and provide repeatable test environments, their use in wireless device testing has increased rapidly. However, as the operating frequencies of wireless devices increase, it becomes essential to study and characterize RCs at these frequencies. This paper presents the characterization of a 60 GHz RC for millimeter-wave (mmWave) wireless testing through key metrics such as the quality factor (Q) and the Rician K-Factor, highlighting the differences with respect to lower frequency ranges. The testing on a real device confirms the results obtained during chamber characterization.

Index Terms—Quality factor, K-factor, reverberation chamber, multipath, wireless device testing, 60 GHz

I. INTRODUCTION

Reverberation chambers (RC) are electrically large metal cavities whose electromagnetic field is statistically uniform, isotropic, and randomly polarized by applying proper stirring techniques [1]. Over the last few years, interest in reverberation chambers and their use in electromagnetic compatibility (EMC) testing has increased rapidly. Standardized procedures and practices for commercial use of these environments are described in the international standard IEC 61000-4-21 [2], which outlines four types of tests: radiated immunity, radiated emission, shielding effectiveness, and antenna efficiency measurements [3] [4] [5] [6]. In addition, RC has been widely proposed as a testing environment for wireless and communication systems [7].

Testing of wireless devices inside these cavities has increased rapidly due to their ability to support multiple reflections (and create multipath signals), stress the device under test, and mimic real propagation conditions [8]. However, due to the higher bandwidth requirements of 5G and 6G wireless devices [9], there is a strong need to characterize the chamber at high frequencies by means of traditional [10] or new performance indicators.

In [11] a small chamber at 60 GHz for animal exposure testing is described, but it is not applicable for wireless device testing due to its small size. Other studies have already confirmed that reverberation chambers are a promising method for Over-the-Air (OTA) testing of 5G devices up to 40 GHz [12] and that they are accurate for testing the 5G FR2 band of user equipment [13], even in very hostile environments [14]. In the present study, we focus on the characterization of a large RC (60 m³) at 60 GHz, able to host real-life devices in

different propagation conditions, also including line-of-sight (LOS) and non-line-of-sight (NLOS) situations.

Our goal is to describe the chamber based on the quality factor (Q) and the Rician K factor. This analysis will help to fully understand the behavior of a reverberation chamber around this frequency. To achieve this, the paper is organized as follows: First, we provide an overview of our experimental setup and the reverberation chamber used. We then characterize it using two metrics: the Q-factor and the Rician K-factor. Finally, to validate the characterization results, measurements using commercial wireless devices operating at 60 GHz are conducted.

II. THE REVERBERATION CHAMBER

The Reverberation Chamber used in the present study is a rectangular metallic cavity fabricated from galvanized steel, with dimensions of $6 \times 4 \times 2.5$ m³. A door of 200 cm $\times$ 95 cm is placed in one of its side walls. Field stirring within the chamber is accomplished through a mechanical stirrer mounted along a horizontal rotational axis, comprising eight irregularly shaped metallic plates. The chamber dimensions are designed to accommodate both transmitting and receiving wireless devices within the working volume during testing. The measurements are performed using a vector network analyzer (VNA) positioned inside the chamber. The reasoning behind this is that the cables used to connect the VNA to the antennas exhibit an attenuation of 10 dB/m. By positioning the VNA inside the chamber, only two cables are required, thereby minimizing losses and ensuring sufficient dynamic range for S-parameter S_{21} (transmission coefficient) measurements. The complete setup is illustrated in Fig. 1.

At the test frequencies of approximately 60 GHz, the RC operates as an electrically large cavity, whose dimensions are significantly large relative to the wavelength ($\lambda \approx 5$ mm). Furthermore, the presence of the VNA within the chamber introduces some loading, which can emulate the presence of the transmitting and receiving devices during realistic testing conditions. Consequently, during the test reported in section IV, the VNA will be removed and substituted by the access points.

III. RESULTS

The quality factor is a critical parameter for characterizing reverberation chambers, as it describes the chamber's ability to store energy. It determines the electromagnetic field level

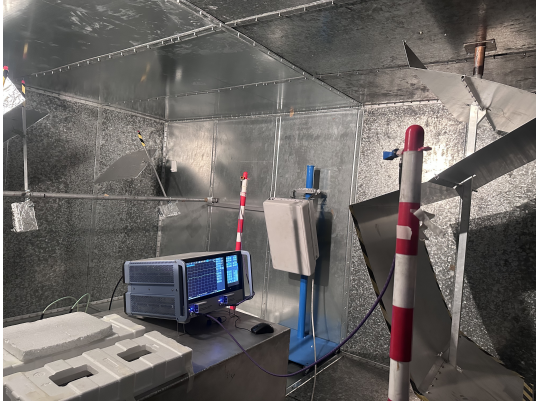


Fig. 1. The test setup used for the 60 GHz measurements in the RC.

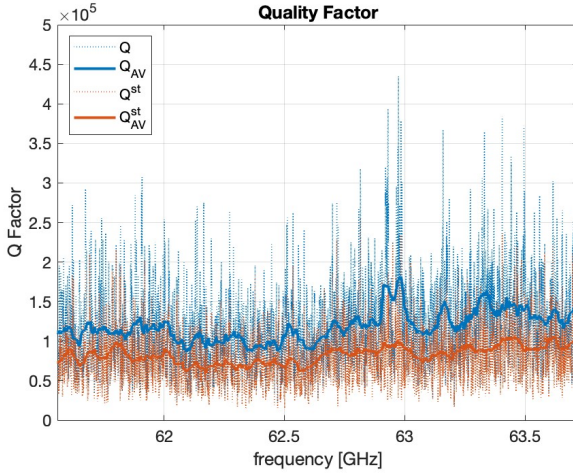


Fig. 2. Quality Factor of the reverberation chamber around 60 GHz, calculated using S_{21} parameter.

established within a well-stirred reverberation chamber for a given input power [15].

Several measurement techniques for evaluating the Q-factor have been proposed in the literature, mainly categorized into frequency-domain and time-domain methods [16].

In this study, the Q-factor is evaluated using frequency-domain techniques based on equation 1 [2], including antenna efficiency corrections to account for real antenna losses.

$$Q = \frac{16\pi^2 V}{\eta_{Tx} \eta_{Rx} \lambda^3} \langle |S_{21}|^2 \rangle, \quad (1)$$

where V is the chamber volume (m^3), λ is the wavelength (m), η_{Tx} and η_{Rx} denote the total antenna efficiency factors for the transmitting and receiving antennas, respectively, and the angular brackets $\langle \rangle$ represent the averaging operator over stirring positions and frequencies [15]. The results are reported in Fig. 2. The quality factor related only to the stirred component Q^{st} , is obtained by substituting S_{21} with its stirred component S_{21}^{st} in equation 1, where S_{21}^{st} is given by equation 2.

$$S_{21}^{st} = S_{21} - \langle S_{21} \rangle. \quad (2)$$

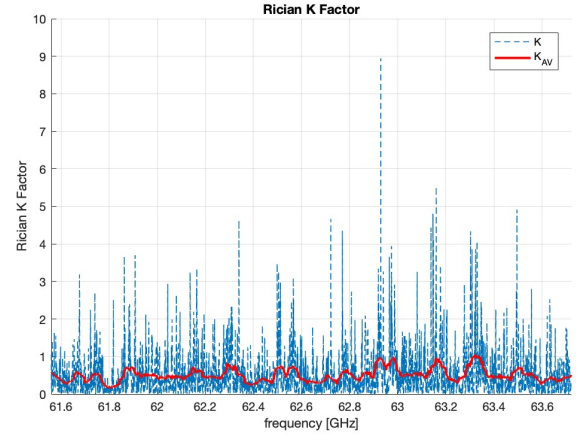


Fig. 3. Rician K-Factor values around 60 GHz.

The results indicate a good quality factor around 60 GHz, with high values ranging between $1 \cdot 10^5$ and $5 \cdot 10^5$. This emphasizes that the RC has good capability of storing energy around this frequency. An averaged value for both the total Q-factor and the Q-factor related to the stirred component is calculated for each frequency ranging between 61.5 GHz and 64 GHz. It is important to note that there is a significant difference between these parameters, which differs from what is typically observed at lower frequencies [17].

Another important parameter in characterizing the RC and understanding if it is imitating a wireless propagation environment, is the Rician K-factor. This parameter describes the ratio between the unstirred energy and the stirred one. Inside the RC, it can be determined as the ratio between the power of the direct path and the power of the scattered components [7] as described in the equation below:

$$K = \frac{(\langle |S_{21}| \rangle)^2}{(|S_{21} - \langle S_{21} \rangle|)^2}, \quad (3)$$

where the angular brackets represent the averaging operator over all chamber field realizations. For wireless testing, it is important to note that a high K-factor value is required to replicate realistic propagation environments for the device under test [18]. The results are shown in figure 3.

The average K-factor across 61.5 GHz - 63.5 GHz range is shown by the solid blue line, while the per-frequency K-factor values are shown as dotted lines. The graph indicates K-factor values varying from 0.16 to 9 over the 61.5 GHz - 63.5 GHz range. For comparison, in lower-frequency RC studies (e.g., 0.4 GHz - 2.4 GHz), the reported Rician K-factor is typically between 0.05 - 1.5 [8]. This means that at 60 GHz, the stirred field has lower weight, and the multipath effect is enhanced. This improves the reproduction of complex real-life environment for wireless device testing.

To further assess the chamber's behavior at 60 GHz, we performed a set of experiments to quantify the total quality factor and the quality factor of the stirred-field component (Q^{st}) by modifying the chamber loading. Figure 4 compares

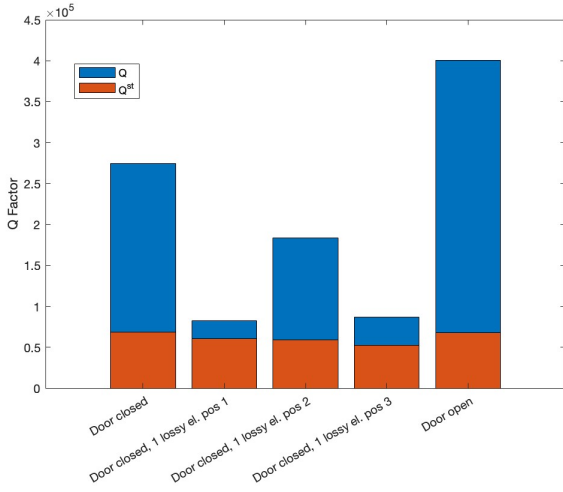


Fig. 4. Total quality factor and stirred component (Q^{st}) measured for five different scenarios.

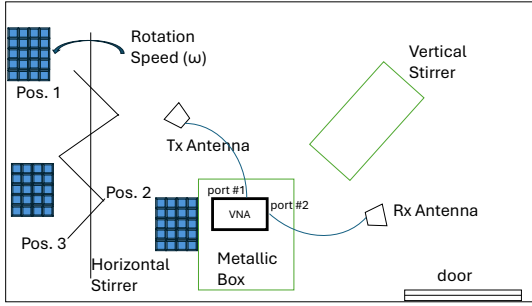


Fig. 5. Measurement scenario, including losses positions

Q and Q^{st} under different conditions: with the chamber door closed, with lossy loads (one VHP-8-NRL absorbing panel) placed at three different locations inside the chamber (see Fig. 5), and with the door open.

Overall, the Q^{st} values are consistent across all configurations ($\approx 0.5 \cdot 10^5$), whereas the total Q varies significantly. This suggests that, at 60 GHz, the stirred field is almost unaffected by lossy objects or open door, in contrast to the total field quality factor. We observe that the highest Q -factor is measured in the door-open condition, where Q^{st} is approximately $0.6 \cdot 10^5$ and the total Q is $4 \cdot 10^5$.

By inserting a lossy object into the chamber and varying its location, we observe that object placement at 60 GHz significantly influences the chamber's total quality factor. Positioning the load at location 2 nearly doubles the total Q , whereas the stirred-field quality factor remains almost unchanged [19] [20]. A second important observation arises when the chamber door is left open. The expectation is a reduced Q relative to the closed-door condition due to the increased energy leakage from the chamber. However, the opposite behavior is observed: the quality factor increases while the Q^{st} remains almost constant. The open door allows

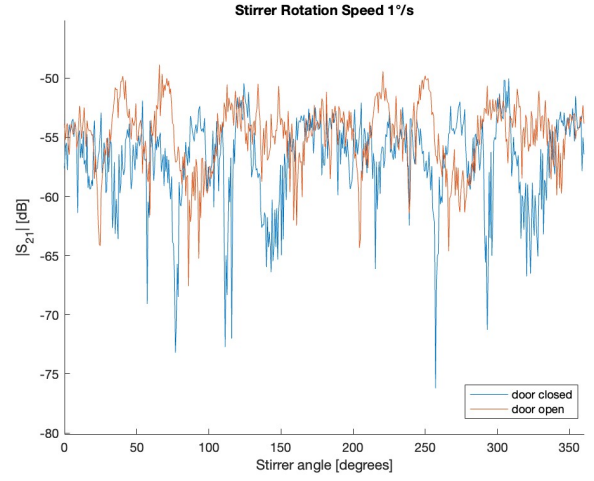


Fig. 6. Measured S_{21} parameter for door open and closed conditions at a stirrer rotation speed of $1^\circ/\text{s}$.

unstirred components to escape through the aperture, reducing their contribution to the measured S_{21} . This increases the total Q , while Q^{st} remains almost constant at approximately $7 \cdot 10^4$. This interpretation is supported by S_{21} measurements for both scenarios, shown in Figure 6.

During the stirrer rotation, there are many time slots where the open-door S_{21} is higher. It is important to note that the RC is not operating as expected. There is a significant difference between the total Q and the Q^{st} , despite the fact that the RC is operating at a very high frequency, where a large number of modes are excited. While this deviates from the ideal Rayleigh environment required for EMC standardized testing, the high Q values demonstrate rich multipath propagation. This aspect is further confirmed by a lower stirring ratio with respect to lower frequencies in the same chamber [8]. This environment may therefore be suitable for testing wireless devices that operate in real-world environments containing high multipath components. In the next section, we validate this characterization by testing wireless devices operating at 60 GHz inside this environment.

IV. TEST ON REAL WIRELESS DEVICES

To further validate the chamber characterization at 60 GHz, the measurements were repeated using two commercial wireless devices operating at this frequency. A V1000 [21] fixed wireless node (acting as a transmitter) and a V5000 [22] distribution node (acting as a receiver), both shown in Figure 7, replacing the test antennas and the VNA, and positioned in a non-line-of-sight configuration. The complete experimental setup is shown in Figure 8.

The parameter used to validate the characterization results shown in the previous section is the Received Signal Strength Indicator (RSSI), which quantifies the power of the wireless signal received by the device. In our case, it indicates the signal strength received by the V5000 when the V1000 transmits at a fixed power of 13 dBm. Tests were performed under four



Fig. 7. V1000 fixed wireless node (a) and V5000 distribution node (b)

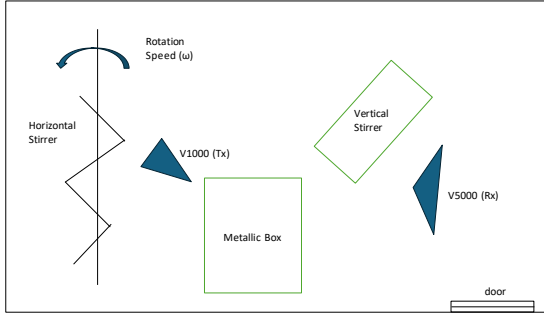


Fig. 8. Experimental setup of the RC operating at 60 GHz with two wireless devices positioned in non-line-of-sight (NLOS) configuration.

conditions: the stirrer rotation speed was first set to 10 degrees per second, and measurements were taken with the RC door open and closed. The experiment was then repeated with the stirrer rotation speed set to 2 degrees per second. The RSSI measurements for stirrer speeds of 2°/s and 10°/s are shown in Figures 9 and 10, respectively.

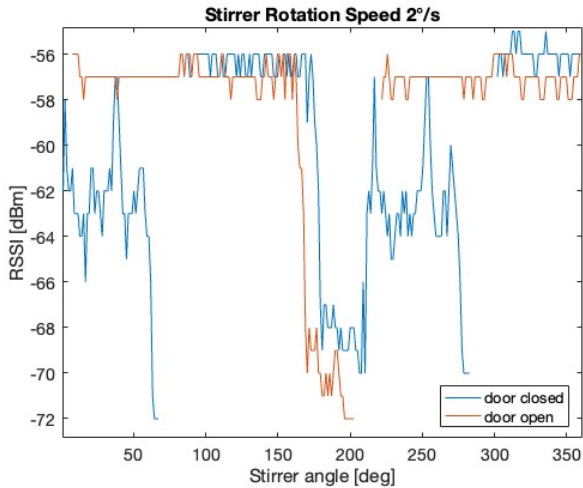


Fig. 9. RSSI measured over time for door open and closed conditions (stirrer speed: 2°/s).

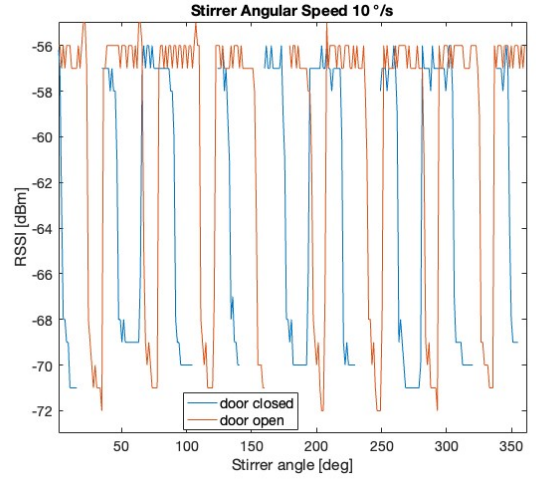


Fig. 10. RSSI measured over time for door open and closed conditions (stirrer speed: 10°/s).

When the stirrer speed is increased to 10°/s, both configurations (door open and closed) show significant RSSI fluctuations. However, it can be observed that when the door is closed the time intervals with an higher RSSI value exhibit a lower duration. This behavior is due to a highly dynamic multipath environment inside the RC, which causes significant variations in the received signal strength [23]. The more dynamic the environment, the greater the fluctuation – a relationship further confirmed by the increased variation observed at the higher stirrer rotation speed. Two important conclusions can be drawn from these results: First, the operation of the reverberation chamber at 60 GHz creates a rich multipath environment that stresses the wireless device, producing deep fluctuations in received power similar to those experienced in real-world multipath environments. This is further supported by the measured Q-factor and K-factor values presented in the previous section. Second, the door-open scenario and the corresponding RSSI measurements validate the S_{21} measurements from the previous section. Specifically, opening the door increases the time-averaged RSSI (analogous to the increased S_{21}).

V. CONCLUSION

In this paper, we have characterized a reverberation chamber operating at 60 GHz for wireless device testing by measuring the S_{21} parameter and calculating the Q-factor and the Rician K-factor of the chamber. We have concluded that reverberation chambers operating at 60 GHz can provide a rich multipath environment for wireless device testing, achieving a high Q-factor ($Q^{st} \approx 7 \cdot 10^4$ and total $Q \approx 2.75 \cdot 10^5$). However, the chamber contains a large number of unstirred components, indicated by elevated K-factor values and a large difference between the total Q and the stirred Q^{st} . The environment is also highly sensitive to object positioning and exhibits unusual behavior when introducing large apertures, such as opening the RC door. The total Q-factor increases, while Q^{st} remains almost constant, which is not the expected behavior

for well-stirred RCs. Nevertheless, the environment is suitable for stressing the wireless device under test, creating a realistic multipath environment similar to real-world scenarios. This is also supported by RSSI measurements with commercial 60 GHz devices.

In future work, we intend to conduct additional measurements to investigate the impact of object positioning when the chamber door is open. Unlike traditional EMC tests, where results are typically expected to be insensitive to objects positioning, replicating real-life propagation environments requires the RC to deviate from the ideal behavior. Furthermore, a comparison with lower frequency ranges is planned, with the aim of defining specific performance indicators for the use of reverberation chambers in millimeter-wave testing. This analysis will also include an accurate check of field statistics in terms of distribution and correlation.

ACKNOWLEDGMENT

This work is supported by MSCA TMA DN NEPIT- Network for Evaluation of Propagation and Interference Training. This project has received funding from the European Union's Horizon Europe - Research and Innovation program - under grant agreement no. 101119806.

REFERENCES

- [1] R. Serra, A. C. Marvin, F. Moglie, V. M. Primiani, A. Cozza, L. R. Arnaut, Y. Huang, M. O. Hatfield, M. Klingler, and F. Leferink, "Reverberation chambers a la carte: An overview of the different mode-stirring techniques," *IEEE Electromagnetic Compatibility Magazine*, vol. 6, no. 1, pp. 63–78, 2017.
- [2] *Electromagnetic compatibility (EMC) - Part 4-21: Testing and measurement techniques - Reverberation chamber test methods*, 2nd ed., International Standards - IEC 61000-4-21, Geneva, Switzerland, Apr. 2011.
- [3] C. L. Holloway, H. A. Shah, R. J. Pirkel, W. F. Young, D. A. Hill, and J. Ladbury, "Reverberation chamber techniques for determining the radiation and total efficiency of antennas," *IEEE Transactions on Antennas and Propagation*, vol. 60, no. 4, pp. 1758–1770, 2012.
- [4] W. Krouka, F. Sarrazin, J. Sol, P. Besnier, and E. Richalot, "Comparison of antenna radiation efficiency measurement techniques in reverberation chamber using or not a reference antenna," in *2020 14th European Conference on Antennas and Propagation (EuCAP)*, 2020, pp. 1–4.
- [5] W. Qi, Y. Zhao, W. Xia, F. Fang, C. Li, L. Xing, and Q. Xu, "A fast time-domain method of antenna efficiency measurement in a reverberation chamber," *IEEE Antennas and Wireless Propagation Letters*, vol. 22, no. 7, pp. 1682–1685, 2023.
- [6] C. Carobbi and D. Masiero, "Measurement of antenna efficiency in reverberation chamber - effect of loading," in *2024 IEEE INC-USNC-URSI Radio Science Meeting (Joint with AP-S Symposium)*, 2024, pp. 349–350.
- [7] C. L. Holloway, D. A. Hill, J. M. Ladbury, P. F. Wilson, G. Koepke, and J. Coder, "On the use of reverberation chambers to simulate a rician radio environment for the testing of wireless devices," *IEEE Transactions on Antennas and Propagation*, vol. 54, no. 11, pp. 3167–3177, 2006.
- [8] V. M. Primiani, M. Barazzetta, L. Bastianelli, D. Micheli, F. Moglie, R. Diamanti, and G. Gradoni, "Reverberation chambers for testing wireless devices and systems," *IEEE Electromagnetic Compatibility Magazine*, vol. 9, no. 2, pp. 45–55, 2020.
- [9] A. Hubbrechtsen, L. A. Bronckers, S. J. Verwer, A. C. F. Reniers, and A. B. Smolders, "A reverberation chamber for antenna measurements up to 140 GHz," *IEEE Transactions on Antennas and Propagation*, vol. 72, no. 5, pp. 4000–4009, 2024.
- [10] R. Serra, "Reverberation chambers through the magnifying glass: an overview and classification of performance indicators," *IEEE Electromagnetic Compatibility Magazine*, vol. 6, no. 2, pp. 76–88, Jul. 2017.
- [11] A. K. Fall, P. Besnier, C. Lemoine, M. Zhadobov, and R. Sauleau, "Design and experimental validation of a mode-stirred reverberation chamber at millimeter waves," *IEEE Transactions on Electromagnetic Compatibility*, vol. 57, no. 1, pp. 12–21, 2015.
- [12] C. S. Patané Lötbäck, "Extending the frequency range of reverberation chamber to millimeter waves for 5G over-the-air testing," in *2017 11th European Conference on Antennas and Propagation (EUCAP)*, 2017, pp. 3012–3016.
- [13] Z. Wang, Y. Ren, Y. Zhang, C. Pan, and X. Zhang, "A novel mode-stirred reverberation chamber design for 5G millimeter wave bands," *IEEE Access*, vol. 9, pp. 38 826–38 832, 2021.
- [14] L. Bastianelli, R. Diamanti, A. de Leo, E. Colella, M. Colombo, V. Mariani Primiani, F. Moglie, and D. Micheli, "Investigation of water and mud effects on the propagation of real 5G signal by using the reverberation chamber," *IEEE Access*, vol. 13, pp. 121 868–121 879, 2025.
- [15] J. C. West, J. N. Dixon, N. Nourshamsi, D. K. Das, and C. F. Bunting, "Best practices in measuring the quality factor of a reverberation chamber," *IEEE Transactions on Electromagnetic Compatibility*, vol. 60, no. 3, pp. 564–571, 2018.
- [16] J. Yousaf, W. Nah, M. I. Hussein, J. G. Yang, A. Altaf, and M. Elahi, "Characterization of reverberation chamber - a comprehensive review," *IEEE Access*, vol. 8, pp. 226 591–226 608, 2020.
- [17] M. Barazzetta, D. Micheli, F. Moglie, and V. M. Primiani, "Over-the-air performance testing of a real 4G LTE base station in a reverberation chamber," in *2014 IEEE International Symposium on Electromagnetic Compatibility (EMC)*, 2014, pp. 903–908.
- [18] A. De Leo, R. Serra, P. Russo, and V. M. Primiani, "Rician K factor tuning for 5G channel emulation in different typologies of reverberation chambers," in *2023 International Symposium on Electromagnetic Compatibility - EMC Europe*, 2023, pp. 1–6.
- [19] L. Bastianelli, L. Giacometti, V. M. Primiani, and F. Moglie, "Effect of absorber number and positioning on the power delay profile of a reverberation chamber," in *2015 IEEE International Symposium on Electromagnetic Compatibility (EMC)*, 2015, pp. 422–427.
- [20] A. D. Leo, P. Russo, and V. M. Primiani, "Rician K factor fluctuation in reverberation chambers," in *2024 International Symposium on Electromagnetic Compatibility - EMC Europe*, 2024, pp. 1139–1144.
- [21] Cambium Networks. (2025, Apr.) cnWave 60 GHz V1000 Client Node. Accessed: Oct. 9, 2025. [Online]. Available: <https://www.cambiumnetworks.com/products/cnwave/60-ghz-cnwave-v1000/>
- [22] Cambium Networks. (2025, Aug.) cnWave 60 GHz V5000 Distribution Node. Accessed: Oct. 9, 2025. [Online]. Available: <https://www.cambiumnetworks.com/products/cnwave/60-ghz-cnwave-v5000/>
- [23] M. H. Rehmani, A. Rachedi, S. Lohier, T. Alves, and B. Pousso, "On the feasibility of making intelligent antenna selection decision in IEEE 802.15.4 wireless sensor networks," in *2013 Computing, Communications and IT Applications Conference (ComComAp)*, 2013, pp. 41–46.