# Report of "Simulating the Multipath Channel With a Reverberation Chamber: Application to Bit Error Rate Measurements"

DOUADI Khaled // Nivine ALHARISS
Master Syscom, Sorbonne University

***Abstract*—This paper summarizes research on using reverberation chambers to simulate multipath wireless environments. The study explores the chamber's capability to model channel properties like power delay profile (PDP) and root mean square (RMS) delay spread and evaluates their impact on bit error rate (BER) measurements for wireless communication systems.**

## I. Introduction

Wireless communication systems operate in diverse environments with varying propagation characteristics. Testing these systems requires repeatable environments to simulate effects like multipath fading and Doppler spread. Reverberation chambers, initially developed for electromagnetic compatibility (EMC) testing, have emerged as effective tools for simulating multipath channels by enabling controlled manipulation of channel properties.

Unlike anechoic chambers, which require numerous measurements at various orientations to replicate isotropic conditions, reverberation chambers achieve statistical uniformity through rotating mode stirrers. This significantly reduces the time and complexity of testing, as the isotropic field distribution eliminates the need for repeated measurements across different angles or positions. Consequently, reverberation chambers provide a more efficient alternative for simulating wireless environments while maintaining accuracy and repeatability.

## II. Wireless Environment Characterization

In this study, the authors modeled the wireless multipath channel as a time-varying, discrete-time impulse response to simulate and analyze the effects of multipath propagation. Specifically, they assumed that multipath reflections could be represented as delayed and scaled replicas of the transmitted signal. This assumption forms the basis for modeling the channel as a summation of impulse responses at discrete time intervals.

The channel's impulse response, $h(t, \tau)$, was mathematically expressed as:

$$y(t) = \int_{-\infty}^{\infty} h(t, \tau) u(t - \tau) d\tau, \tag{1}$$

where $u(t)$ represents the transmitted signal, $y(t)$ is the received signal, $\tau$ is the excess delay, and $h(t, \tau)$ captures the amplitude and phase changes introduced by the channel.

The ensemble average of the squared magnitudes of the impulse response was calculated to derive the Power Delay Profile (PDP):

$$\mathrm{PDP}(t) = \langle |h(t, \tau)|^2 \rangle. \tag{2}$$

From the PDP, the RMS delay spread, $\tau_{\mathrm{rms}}$, was computed to quantify the channel's dispersion:

$$\tau_{\mathrm{rms}} = \sqrt{\frac{\int_0^{\infty} (t - \tau_0)^2 \mathrm{PDP}(t) dt}{\int_0^{\infty} \mathrm{PDP}(t) dt}}, \tag{3}$$

where $\tau_0$, the mean delay, is given by:

$$\tau_0 = \frac{\int_0^{\infty} t\, \mathrm{PDP}(t)\, dt}{\int_0^{\infty} \mathrm{PDP}(t)\, dt}. \tag{4}$$

To validate the assumptions and develop the model, measurements were conducted in the reverberation chamber. The chamber's ability to generate realistic multipath environments was confirmed by comparing the PDPs and $\tau_{\mathrm{rms}}$ values against theoretical predictions and real-world scenarios. These comparisons allowed the authors to refine their model and establish its applicability for simulating wireless environments with varying levels of multipath interference.

Through this approach, the authors demonstrated that the reverberation chamber could effectively replicate a wide range of multipath environments using a combination of modeled impulse responses and controlled chamber configurations. This provided a foundation for analyzing the impact of channel properties on wireless system performance.

## III. Controlling RMS Delay Spread in the Reverberation Chamber

In this study, the authors explored methods to control the RMS delay spread ($\tau_{\mathrm{rms}}$) in the reverberation chamber to simulate diverse wireless environments with varying multipath characteristics. The reverberation chamber's flexibility lies in its ability to manipulate its quality factor ($Q$) and chamber loading, which directly influence $\tau_{\mathrm{rms}}$.

The quality factor $Q$ is a measure of the chamber's ability to store energy relative to the energy dissipated per RF cycle, defined as:

$$Q = \frac{\omega U}{\langle P_d \rangle}, \tag{5}$$

where $\omega$ is the angular frequency, $U$ is the stored energy, and $P_d$ is the dissipated power.

Additionally, the threshold quality factor ($Q_{\text{thr}}$) represents the minimum quality factor required to maintain spatial uniformity within the chamber. This threshold ensures accurate and reliable field uniformity during measurements, enabling the effective simulation of various wireless environments.

$$Q_{\text{thr}} = \left(\frac{4\pi}{3}\right)^{2/3} \frac{3V^{1/3}}{2\lambda};$$

### A. ***Key Experiment Steps***

*1) Chamber Configuration and Loading:* The experiment involved systematically varying the chamber's loading by introducing RF absorbers. Increasing the number of absorbers reduced the chamber's ring-down duration and decreased $\tau_{\text{rms}}$. This approach allowed the chamber's response to emulate environments with specific delay spreads.

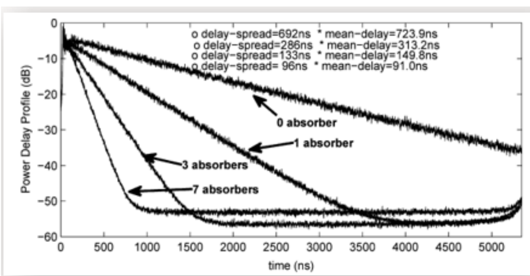



Fig. 1: Measured Power Delay Profile (PDP) for different numbers of absorbers. [1]

*2) RMS Delay Spread Dependence on Frequency and Absorber Count:* The impact of frequency and absorber count on $\tau_{\text{rms}}$ was analyzed. With 0 absorbers, $\tau_{\text{rms}}$ exhibited significant frequency dependence. Adding absorbers (1, 3, 7) reduced reflections and time delay spread, making $\tau_{\text{rms}}$ nearly frequency-independent. At higher frequencies (around 9 GHz), the noise floor impacted results, especially with a higher number of absorbers.

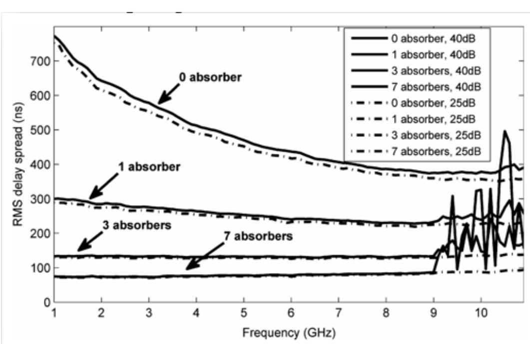



Fig. 2: Measured RMS delay spread as a function of frequency and absorber count [1].

### B. *Findings and Observations*

*1) Impact of Loading on Delay Spread:* Increasing the number of absorbers resulted in shorter delay spreads, simulating environments like office buildings with limited multipath. Conversely, minimal loading maintained longer delay spreads, replicating highly reflective environments such as industrial sites.

*2) Frequency Dependence:* For low absorber counts, $\tau_{\text{rms}}$ exhibited significant frequency dependence, consistent with theoretical predictions. With increased absorbers, the delay spread became nearly frequency-independent, aligning with the expected behavior as $Q$ decreases.

$$\tau_{\text{rms}} = \frac{1}{C_1\sqrt{f} + C_2 N \sigma_{\text{absorber}} + (C_3/f^2)}. \tag{6}$$

where $C_1$ represents antenna loss, $C_2$ accounts for absorber effects, and $C_3$ models low-frequency losses.

*3) Validation of Model and Chamber Time Constant:* The relationship between $\tau_{\text{rms}}$ and the chamber's time constant $\tau$ ($\tau = Q/\omega$) was analyzed using a theoretical model:

$$\tau_{\text{rms}} = \frac{Q}{\omega}\sqrt{\frac{(2\alpha\ln(\alpha)-2\alpha+2-\alpha(\ln(\alpha))^2)^2}{(1-\alpha)} - \frac{(\alpha\ln(\alpha)-\alpha+1)^2}{(1-\alpha)^2}}. \tag{7}$$

For ideal PDP, this simplifies to $\tau_{\text{rms}} = Q/\omega$, showing a linear proportionality between $\tau_{\text{rms}}$ and $Q/\omega$. Experimental results matched theoretical predictions, confirming the chamber's accuracy in simulating various propagation conditions.

### C. *Utility of the Approach*

By combining controlled loading and theoretical analysis, the authors demonstrated the ability of the reverberation chamber to replicate diverse propagation conditions. This makes it a valuable tool for evaluating and optimizing wireless systems in controlled, repeatable environments.

## IV. Bit Error Rate (BER) Measurements

The authors conducted detailed Bit Error Rate (BER) measurements to assess the performance of wireless systems under controlled multipath conditions simulated by the reverberation chamber. BER serves as a critical metric to evaluate the reliability of digital communication systems, especially in multipath environments.

The relationship between BER and channel characteristics such as the RMS delay spread ($\tau_{\text{rms}}$) and the symbol period ($T$) is key to understanding system performance. Mathematically, the BER is proportional to the square of the ratio:

$$\text{BER} \propto \left(\frac{\tau_{\text{rms}}}{T}\right)^2. \tag{8}$$

### A. *Experimental Setup*

The BER experiments were conducted using a vector signal generator (VSG) and a vector signal analyzer (VSA). The VSG was used to generate digitally modulated signals, such as BPSK, at various symbol rates and carrier frequencies. The transmitted signals were then propagated through the reverberation chamber. The VSA at the receiver end demodulated the signals and compared the received bit sequence to the transmitted sequence to calculate the BER.

*1) Test Configuration:* The reverberation chamber was configured with different loading levels (varying numbers of RF absorbers) and paddle speeds. These variations enabled the simulation of different multipath environments and fading conditions. Key parameters included:

- Symbol rates ranging from low to high (e.g., 24.3 ksps to 768 ksps).
- Paddle speeds to control fading and Doppler spread.
- Adjustable loading to modify $\tau_{\text{rms}}$.

### B. Findings and Observations

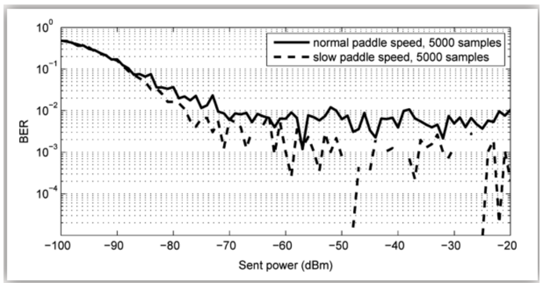
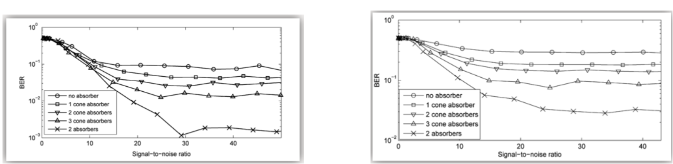



Fig. 3: BER vs Sent Power for normal and slow paddle speeds with 5000 samples [1].

*1) Impact of Paddle Speed:* The paddle speed in the chamber was found to significantly affect the fading characteristics and, consequently, the BER:

- Faster paddle speeds increased the rate of fading, resulting in higher BER due to rapid changes in the channel.
- Slower paddle speeds minimized fading, allowing the channel to behave more like a static multipath environment. This reduced the BER for high-SNR scenarios.



(a) BER vs SNR for 243 ksps.

(b) BER vs SNR for 768 ksps.

Fig. 4: Comparison of BER vs SNR for different symbol rates and absorber configurations [1].

*2) Effect of Chamber Loading:* The number of RF absorbers in the chamber directly influenced $\tau_{\text{rms}}$ and BER performance:

- Fewer absorbers resulted in longer $\tau_{\text{rms}}$, increasing BER, particularly at higher data rates where $T$ was shorter.
- Increasing the number of absorbers reduced $\tau_{\text{rms}}$, significantly lowering BER by mitigating the effects of delayed multipath components.

*3) High Data Rates and Irreducible BER:* At higher data rates, the symbol period $T$ becomes smaller, increasing the sensitivity of the system to $\tau_{\text{rms}}$. This led to the observation of an irreducible BER, even at high SNR values. The irreducible BER was attributed to:

- The inability of the receiver to resolve closely spaced multipath components.
- The residual effects of fading in certain chamber configurations.

### C. Significance of the Results

The experiments demonstrated that the reverberation chamber could accurately replicate a variety of multipath conditions, including high-fading and static environments. By varying paddle speed, loading, and symbol rates, the chamber provided valuable insights into the interplay between $\tau_{\text{rms}}$ and BER.

The findings validate the chamber as a robust and efficient tool for evaluating wireless communication system performance under controlled and repeatable conditions. It enables precise analysis of channel behavior and BER trends without the need for extensive field testing.

## V. Comparisons with Real-World Environments

### A. Real-World Environments Studied

- **Highly Reflective Oil Refinery:** A large industrial site with extensive metallic structures, piping, and ductwork.
- **60-Storied Office Building:** An urban steel and concrete structure with large open areas.

### B. Comparison with Oil Refinery (Industrial Environment)

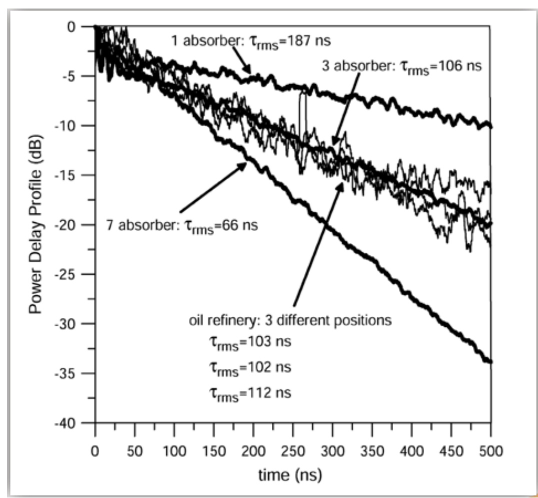



Fig. 5: Comparison of the PDP measured in the reverberation chamber for different amounts of absorber loading to the PDP measured in an oil refinery outside Denver, Colorado. [1].

**Key Observations:**

- PDP in the oil refinery shows **high multipath effects** and a **long decay time**.
- Chamber PDP with **3 absorbers** best matches the industrial environment (Fig. 5).

**Results:**

- $\tau_{\text{rms}}$ in the chamber with 3 absorbers is comparable to that in the oil refinery.
- Adjusting absorber levels allows the chamber to replicate industrial environments effectively.

### C. Comparison with Office Building (Urban Environment)

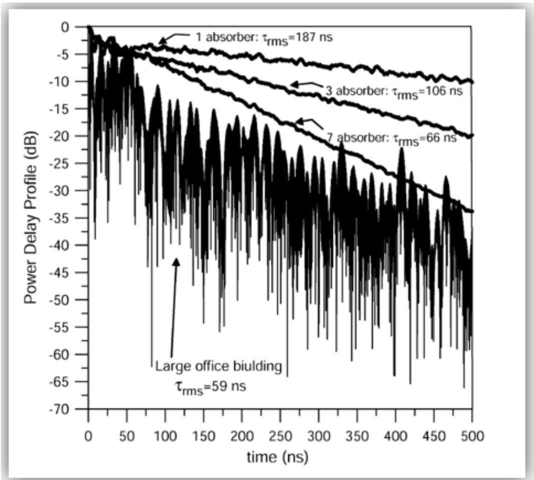



Fig. 6: Comparison of the PDP measured in the reverberation chamber for different amounts of absorber loading to the PDP measured in a 60-storied office building in Denver, Colorado. [1].

**Key Observations:**

- PDP in the office building shows **low multipath effects** and a **short decay time**.
- Chamber PDP with **7 absorbers** best matches the urban environment (Fig. 6).

**Results:**

- $\tau_{\rm rms}$ in the chamber with 7 absorbers aligns with that in the office building.
- Increased chamber loading (more absorbers) reduces multipath effects, simulating low-multipath environments.

### D. BER Comparisons: Reverberation Chamber vs. Real Room

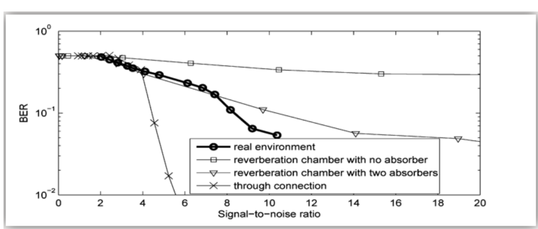



Fig. 7: Comparison of measured BER results from the reverberation chamber and from an office environment for a BPSK data rate of 768 ksps. [1].

**Real Environment Studied:**

- A NIST laboratory room (5 m $\times$ 7 m $\times$ 2.5 m) with cinder block walls, windows, concrete floor, and overhead piping/wiring.

**Setup:**

- BPSK-modulated signal at 768 ksps.
- BER measured across 10 receiving positions and averaged.

**Key Results:**

- **Higher BER values:** Chamber measurements closely match real environment results.
- **Lower BER values:** Chamber measurements deviate slightly due to the challenges of simulating low-multipath environments in the chamber.

## VI. Conclusion

Reverberation chambers effectively simulate real-world wireless environments with adjustable parameters like Power Delay Profile (PDP) and RMS delay spread. Loading the chamber with RF absorbers impacts PDP decay and RMS delay spread, allowing tailored simulation of multipath effects. BER measurements indicate significant dependence on chamber parameters, such as paddle speed and absorber count, and closely match real-world environments. Reverberation chambers provide a reliable and efficient alternative to traditional methods for testing wireless devices under multipath conditions. Future research should explore cluster-based PDP simulations for more complex environments and investigate the effects of modulation schemes, data rates, and advanced access technologies.

## References

[1] E. Genender, C. L. Holloway, K. A. Remley, J. M. Ladbury, G. Koepke, and H. Garbe, “Simulating the Multipath Channel With a Reverberation Chamber: Application to Bit Error Rate Measurements,” *IEEE Transactions on Electromagnetic Compatibility*, vol. 52, no. 4, pp. 766-777, Nov. 2010.